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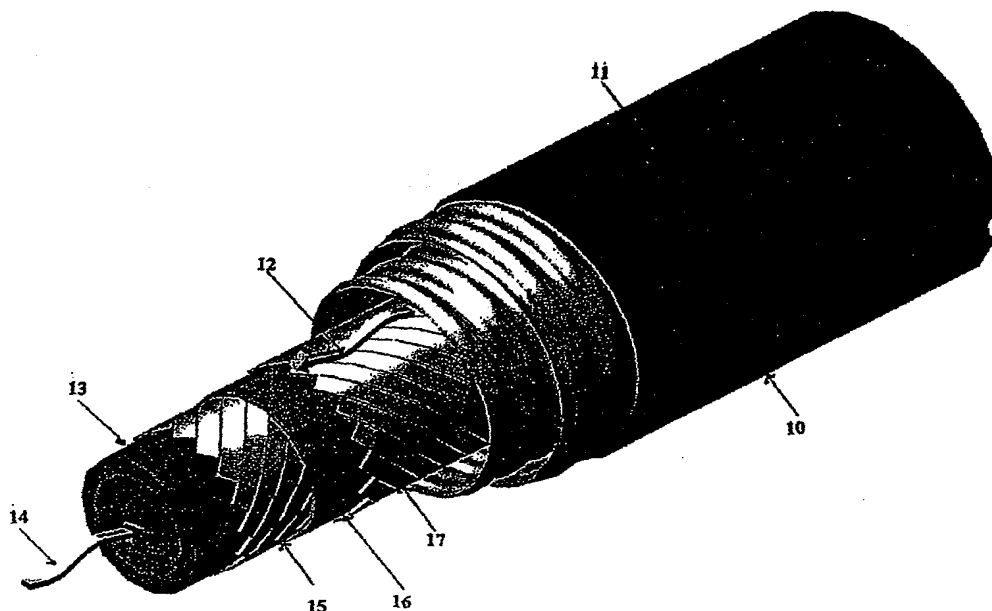
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(54) Title: SUPERCONDUCTING CABLE



(57) Abstract: On order to provide a flexible oxide superconducting cable which is reduced in AC loss, tape-shaped superconducting wires covered with a stabilizing metal are wound on a flexible former. The superconducting wires are preferably laid on the former at a bending strain of not more than 0.2%. In laying on the former, a number of type-shaped superconducting wires are laid on a core member in a side-by-side manner, to form a first layer. A prescribed number of tape-shaped superconducting wires are laid on top of the first layer in a side-by-side manner, to form a second layer. The former may be made of a metal, plastic, reinforced plastic, polymer, or a composite and provides flexibility to the superconducting wires and the cable formed therewith.

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**SUPERCONDUCTING CABLE****BACKGROUND OF THE INVENTION****FIELD OF THE INVENTION**

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The present invention relates to a superconducting cable employing a flexible oxide superconductor, and more particularly, it relates to forming a superconducting cable.

**DESCRIPTION OF THE BACKGROUND ART**

15

Superconducting materials are those where the electric resistance approaches zero (1uv/cm) below a critical temperature, its value depending on the material. Superconductivity is defined within a critical surface, i.e. a graph or figure with its axes being temperature, electrical current and magnetic field. Thus, for a given  
20 working temperature there is a defined curve of critical current which is a function of the magnetic field generated and/or applied to the superconductor.

The best known superconductor materials are NbTi and Nb<sub>3</sub>Sn, however their working temperature is only 4.2K, the boiling temperature of liquid helium. This is  
25 the main limitation to large scale application of these superconducting materials. Such superconductors are therefore used almost exclusively for winding of magnets. Manufactured from wires (NbTi and Nb<sub>3</sub>Sn) or tapes (Nb<sub>3</sub>Sn) with high critical current densities (3500 A/mm<sup>2</sup> 5 Tesla for NbTi), such winding of compact magnets provide the production of high fields (up to 18 Tesla) in large volumes.

30

These superconductor magnets are used for the formation of medical images by nuclear magnetic resonance (MRI) and for materials analysis by the same principle (NMR), the magnets for ore separation and research magnets for high fields, such as those used in large particle accelerators (SSC, HERA, KEK, etc.).

35 Oxide superconductors of higher critical temperatures were discovered in 1986. These are intermetallic compounds involving metal oxides and rare earths, with

5 perovskite (mica) crystal structure. Their critical temperatures vary from 30K to approaching room temperature and their critical fields are above 60 Tesla. Therefore these materials are considered promising and may replace Nb<sub>3</sub>Sn and NbTi in the manufacture of magnets and find other applications not feasible with liquid helium, such as transmission of electricity. Such materials have not previously been available  
10 as wires, cables, films, tapes or sheets.

An oxide superconductor which enters the superconducting state at the temperature of liquid nitrogen would be advantageous for application in a superconducting cable having a cooling medium of liquid nitrogen. With such an application, it would be  
15 possible to simultaneously attain simplification of the thermal protection system and reduction of the cooling cost in relation to a superconducting cable which requires liquid helium.

A superconducting cable must be capable of transmitting high current with low  
20 energy loss in a compact conductor. Power transmission is generally made through an alternating current, and a superconductor employed under an alternating current would inevitably be accompanied by energy loss, generically called AC loss. AC losses such as hysteresis loss, coupling loss, or eddy current loss depends on the critical current density of the superconductor, size of filaments, the structure of the  
25 conductor, and the like.

Various types of superconducting cables have been experimentally produced using metallic superconductors to study the structures for reducing AC loss, such as a superconductor which comprises a normal conductor and composite multifilamentary  
30 superconductors which are spirally wound along the outer periphery of the normal conductor. The conductor is formed by clockwise and counterclockwise wound layers of composite multifilamentary superconductors, which are alternately superimposed with each other. The directions for winding the conductors are varied every layer for reducing magnetic fields generated in the conductors, thereby reducing  
35 impedance and increasing current carrying capacity thereof. This conductor has a high-resistance or insulating layer between the layers.

5

When a cable conductor is formed using an oxide superconductor, the technique employed in a metal superconductor cannot be used. An oxide superconductor, i.e., a ceramic superconductor, is fragile and weak in mechanical strain compared with a metal superconductor. For example, the prior art discloses a technique of spirally winding superconductors around a normal conductor so that the winding pitch is equal to the diameter of each superconductor. However, when a superconducting wire comprising an oxide superconductor covered with a silver sheath is wound at such a short pitch, there is a high probability that the oxide superconductor will be broken, thereby interrupting the current. When an oxide superconducting wire is extremely bent, its critical current may also be greatly reduced. The cable conductor must be flexible to some extent to facilitate handling. It is also difficult to manufacture a flexible cable conductor from a hard, fragile oxide superconductor.

In the United States, there are approximately 3500 miles of high-voltage underground power cables using copper conductors to provide electricity to large metropolitan areas. These cables are aging, and many will be replaced over the next 20 years. Also, metropolitan areas continue to grow requiring new cable capacity. Electric utility companies are looking for new cable technologies that increase power density, reduce losses and costs while maintaining the high reliability of conventional cables. Superconducting cables have the potential to meet these challenging requirements.

The cost of installing a new cable in a metropolitan area is expensive. The cable accounts for about 30% to 50% of the costs and installation is the major remaining cost. A superconducting cable can replace existing copper cables and increase the power density by a factor of 3 to 8. The existing predominant cable design is a high-pressure oil-filled pipe-type cable consisting of a steel pipe 10.1 to 20.3 cm (4" to 8") in diameter housing three copper cables and oil. These old copper cables and oil can be removed and replaced with superconducting cables with a significantly higher current capability saving the installation costs of a new cable system.

35

- 5 The superconducting cable offers a new application of cables to metropolitan areas. With existing technology, high-voltage copper cables transmit power from the outskirts of cities to the downtown area, where transmission substations lower the voltage and distribution circuits deliver power to customers. With this new superconducting technology, low-voltage high-current superconducting cables can  
10 transmit power to downtown areas, allowing utility companies to move the high-voltage transmission substations out of the downtown area. These substations are very expensive to install and maintain in downtown areas where land costs range from \$100 to \$600 per square foot.
- 15 The present invention has successfully shown the utility application of superconducting cables at distribution voltages and high currents. Potential utility applications include: 1) substation to customer, 2) substation to substation, 3) extended substation bus, 4) substation express feeder, 5) generating unit to step-up transformer.

20

#### SUMMARY OF THE INVENTION

- An object of the present invention is to provide a superconducting cable having flexibility and exhibiting excellent superconductivity, particularly high critical current  
25 and high critical current density, having an oxide superconductor.

Another object of the present invention is to provide such a superconducting cable which is reduced in AC loss.

- 30 According to the present invention a superconducting cable is provided employing an oxide superconductor, which comprises a flexible core member, and a plurality of tape-shaped oxide superconducting wires which are wound on the core member, without an electric insulating layer between the superconducting wires or between the core member and the superconducting wires. In the inventive conductor, each of the  
35 oxide superconducting wires consists essentially of an oxide superconductor and a stabilizing metal covering the same. The plurality of tape-shaped superconducting

- 5 wires laid on the core member form a plurality of layers, each of which is formed by laying a plurality of tape-shaped superconducting wires in a side-by-side manner. The plurality of layers are successively stacked on the core member. This core member provides the inventive superconducting cable with flexibility. The superconducting cable according to the present invention maintains a superconducting state at the  
10 temperature of liquid nitrogen.

The conductor according to the present invention further provides an AC conductor which is reduced in AC loss.

- 15 The foregoing and other objects, features, aspects and advantages of the present invention will become more apparent from the following detailed description of the present invention when taken in conjunction with the accompanying drawings.

#### BRIEF DESCRIPTION OF THE DRAWINGS

20

FIG. 1 is a perspective view showing the multilayer structure of the present invention; FIG. 2 is a sectional side view showing one embodiment of the present invention; FIG. 3 is a sectional side view showing another embodiment of the present invention; FIG. 4 is a depiction of the embossing pattern used in the present invention.

25

#### DESCRIPTION OF THE PREFERRED EMBODIMENTS

- The present invention relates to a high temperature superconductor cable which may be used in the shielded or unshielded form of construction. There are many  
30 applications where both shielded and unshielded cables serve useful purposes.

- A modification of this embodiment is to insulate the cable with dielectrics over the high temperature superconductor tapes and then provide another high temperature superconductor layer over the dielectric. The entire cable is then either introduced  
35 into a cryostat of the type described above or a cryostat is constructed over the cable. This coaxial construction forces the magnetic field to stay between the inner and the

5 outer layers of high temperature superconductor tapes. There is substantially no magnetic field outside the high temperature superconductor tapes and therefore there is no eddy current in the outer metallic enclosures. With this construction very large amounts of current can be carried depending upon the number of tapes present in the cable. The limitation in this cable design is that the dielectric remains at the  
10 cryogenic temperature and a material which can withstand the cryogenic temperature without any physical and mechanical degradation has to be used. The polymeric dielectric material of one embodiment of the present invention has good physical and mechanical properties at liquid nitrogen and lower temperatures. It has high dielectric strength and high breakdown voltage. Advantageously the cable of the present  
15 invention includes the use of a flexible stainless steel corrugated pipe, which is optionally covered with a wire braid or mesh. Preferably, the corrugated pipe is drilled with holes of a size and pattern to allow the liquid nitrogen to flow into the butt gaps of the high temperature superconductor tapes and flood the dielectric material. The high temperature superconductor tapes are laid in a special manner to  
20 simulate two layer construction allowing maximum current to flow through the cable.

The dielectric material advantageously consists of semi-conductive tape, aluminized shield tape, and polymeric dielectric tapes. A typical construction of a shielded cable is shown in Fig. 3. An unshielded cable can be constructed by omitting the outer  
25 layers of high temperature superconductor tapes. This cable construction is shown in Fig. 2. The present invention includes both shielded and unshielded high temperature superconductor cable. The design differs from other known cables in the case of an unshielded cable where an extrusion of dielectric material is performed over the thermal insulation cryostat. The prior art does not disclose any method of  
30 construction for shielded high temperature superconductor cable.

Referring to Fig. 1, superconductor cable 10 is shown having flexible, evacuated double walled, outer pipe 11, through which liquid nitrogen, 12, flows to a chiller. Ground-potential superconductive shield material 17 encircles dielectric and shield  
35 layer 16, which in turn surrounds current carrying superconductive material 15. The flexible, porous-walled inner pipe, 13, is encircled by superconducting material 15



5 and provides a central, tube-like portion for transport of liquid nitrogen from the chiller. In one embodiment pipe 13 further has a braided surface that contacts superconductive material 15.

10 Fig. 2 illustrates an embodiment of an unshielded cable wherein former 21 is surrounded by semiconductive bedding tape 22, upon which is laid superconductive tape 23. Another layer of semiconductive bedding tape 24 surround superconductor tape 23. Shielding layer 25 encircles bedding tape 24 and dielectric layer 26 surrounds shielding layer 25. Dielectric layer 26 is encircled by shield layer 27 which in turn is encircled by semiconductive bedding layer 28. Bedding layer 28 is  
15 surrounded by binder tape 29, which is encompassed by centering ring 30, in turn surrounded by jacketed cryostat 31.

Referring to Fig. 3, which shows an embodiment of a shielded cable, jacketed cryostat 53 encompasses centering ring 52, which surrounds binder tape 51, which in turn  
20 encircles semiconductive tape 50. Tape 50 encircles superconductive tape 49, which surround semiconductive bedding tape 48, which encompass shielding layer 47. Dielectric 46 encircles shield layer 45, which surrounds semiconductive tape 44. Superconductive tape 43 encircles semiconductive bedding tape 42, which surrounds former 41.

25

The present invention relates to a cable employing an oxide superconductor comprising a flexible core member, a plurality of tape-shaped oxide superconducting wires laid on said core member with tension of not more than about  $2 \text{ kgf/mm}^2$  and a bending strain of not more than about 0.2% on the superconductor, wherein each  
30 tape-shaped superconducting wire consists essentially of an oxide superconductor and a stabilizing metal covering the same, said plurality of tape-shaped superconducting wires forming a plurality of layers each being formed by laying said tape-shaped superconducting wires in a side-by-side manner, said plurality of layers being successively stacked on said core member without an insulating layer between the  
35 plurality of layers and the core member, said core member providing said superconducting cable with flexibility, said superconducting cable capable of

5 maintaining a superconducting state at the temperature of liquid nitrogen, said wires having substantially homogeneous superconducting phases along the longitudinal direction of said wire, the c-axes of said superconducting phases being oriented substantially in parallel with the direction of thickness of said wire, said superconducting wires being formed by grains aligned in parallel extending along the  
10 longitudinal direction of said wire, said grains being stacked along the direction of thickness of said wire.

The superconducting cable advantageously has flexibility such that its superconductivity does not substantially deteriorate upon bending up to about 50  
15 times the diameter of the cable. It is also advantageous that the core member be selected from the group consisting essentially of metals, plastics, reinforced plastics, polymers, and composites. One embodiment of the superconducting cable provides a core member being a pipe having a spiral groove surface, a web shaped surface, a mat shaped surface, or a braid shaped surface on its exterior which forms a surface for the  
20 tape-shaped superconducting wires. The inventive superconducting cable does not have any insulating layer between the plurality of layers of the tape-shaped superconducting wires. Advantageously the tape-shaped wires are laid on said core member with the tape-shaped plurality of layers being laid on the surfaces formed by said immediately prior layer of tape-shaped wires. In another embodiment the wires  
25 are twisted within said tape-shaped stabilizing metal covering. Advantageously in the superconducting cable said tape-shaped wires are laid at a lay angle of up to about 90 degrees, advantageously from about 10 to about 60 degrees, and preferably from about 20 to about 40 degrees. One embodiment of the present invention includes a superconducting cable having at least two distinct groups of tape-shaped wire layers.  
30 Advantageously the lay angle of each successive layer of tape-shaped wires alternate in lay direction or pitch; and each said successive layer consists of at least two tape-shaped wires. Advantageously, a layer of dielectric material separates each of the at least two distinct groups of tape-shaped wire layers. Preferably, a layer of dielectric material separates the core member from the layer of tape-shaped wires closest  
35 thereto. Advantageously, the dielectric material is selected from the group consisting of polypropylene, polyethylene, and polybutylene. In one embodiment of the present

5 invention the at least two distinct groups of tape-shaped wire layers carries approximately equal amounts of the current flowing through the cable. Also advantageous is where the group of tape-shaped wire layers furthest from the core member provides shielding of the current flowing through the other layers and reduces magnetic fields or eddy currents in the cable. Preferably, the stabilizing metal  
10 used in the present invention is selected from the group consisting of silver, silver alloys, and nickel and nickel alloys, which may require a buffer layer.

Included in the present invention is an embodiment in which each tape-shaped multifilamentary oxide superconducting wire has such a structure that is a number of  
15 filaments consisting essentially of an oxide superconductor contained in a stabilizing material of silver, silver alloys, nickel and nickel alloys. The oxide superconductor may be prepared from an oxide superconductor such as bismuth, strontium, calcium and copper oxide.

20 Advantageously, each of said plurality of layers contains at least 2 tape-shaped silver contained wires per layer. Preferably, each of said plurality of layers contains at least 4 tape-shaped wires per layer. One embodiment of the present invention includes an insulating layer between the second and third layer of said plurality of layers. Where there are more than 4 layers, advantageously, an insulating layer is present between  
25 each second and third layer of said plurality of layers.

In the inventive conductor, the core member, which is generally called a former, is adapted to hold the tape-shaped superconducting wires at a bending strain of the prescribed range. This former has a length which is required for the superconducting  
30 cable conductor, and is provided at the center of the superconducting cable conductor. The former is in a substantially cylindrical or spiral shape so that the tape wires are laid thereon, and generally has a substantially constant diameter along its overall length. The former can consist essentially of at least one material selected from the group consisting of metals such as stainless steel, copper, aluminum and the like and  
35 plastics, reinforced plastics and ceramics.

5 According to the present invention, the former is preferably in the form of a tubular member having flexibility. It is also possible to employ a pipe having a spiral groove (hereinafter referred to as a spiral tube) as a former having sufficient strength and flexibility. A bellows tube having a bellows may also be employed as a former. Further, the former can also be prepared from a spirally wound material such as a  
10 spiral steel strip. Each of these shapes is adapted to provide the former with sufficient flexibility. The flexible former provides the inventive conductor with flexibility. The flexible conductor of the present invention can be taken up on a drum.

When practicing the present invention, it is possible to lay or wind several  
15 tape-shaped multifilamentary superconducting wires on the former. The tape wires may be laid in two or more layers while directing a surface thereof to the former. Each layer may be formed by an arbitrary number of the tape wires. When several tape wires are laid on the former in parallel with each other so that the surface of the former is filled up with the tape wires, additional tape wires are further wound  
20 thereon. When a sufficient number of tape wires are wound on the first layer of the tape wires as a second layer, a third layer of tape wires are then wound thereon. No insulating layer is provided between each adjacent pair of layers.

In the present inventive method, each tape-shaped multifilamentary oxide  
25 superconducting wire is laid or wound on a former having a prescribed diameter at a bending strain or a curvature of a prescribed range and a pitch of a prescribed range. A relatively loose bending is applied to the tape wire along its longitudinal direction. The tape wire which is wound on the former is bent at a bending strain of not more than 0.4%, preferably not more than 0.3%. Superconductivity of the tape wire is not  
30 substantially reduced upon bending at a bending strain of such a range, as compared with that in a linear state.

The present invention it is preferable to adjust the pitch and the diameter of the former so that the bending strain of the superconductive wire is not more than 0.2%. Each  
35 tape-shaped multifilamentary oxide superconducting wire is preferably wound on the former with tension of not more than  $2 \text{ kgf/mm}^{-2}$  in a range of  $0.5$  to  $2 \text{ kgf/mm}^{-2}$ .

5

The core member (former) can be formed by either an electric insulating material or an electric conductor. The electric insulating material is preferable in consideration of reduction in AC loss, while a metal which is a conductor is preferable in consideration of strength. A metal pipe having a spiral groove or a metal bellows tube may be used as the core member for providing the conductor with flexibility while maintaining constant strength. A metal core member can also be employed for safety in the case of an accidental abnormal current. In this case, it is possible to set optimum resistivity of the core member in consideration of AC loss of the conductor and the core member for the abnormal current.

15

When a metal pipe, which optionally may have a spiral groove, or a metal bellows tube is employed as the core member, the conductor can further comprise a metal tape which is laid or wound on the core member, and dielectric tape which is laid on a the outside surface of the metal tape. The metal tape can form a smooth surface for covering any grooves of the core member so that the superconducting tapes do not buckle. It is possible to cover any grooves while maintaining flexibility of the core member by laying the metal tape.

25

According to the present invention, it is possible to employ tape-shaped multifilamentary wires each having twisted filaments. The filaments forming a superconducting multifilamentary tape are twisted at a prescribed pitch. Due to such twisting of the filaments, an induction current flowing between a stabilizing metal and the filaments is parted every twisting pitch into small loops, and hence the value of the current is limited. Thus, generation of Joule heat is suppressed in the stabilizing metal and AC loss is reduced as compared with a superconducting wire having untwisted filaments.

30

The superconducting cable conductor according to the present invention has such flexibility that its superconductivity is substantially not deteriorated also when the same is bent up to 50 times the diameter of the cable. This conductor can be wound on a drum, to be stored and/or transported.

35

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The present invention also makes it is possible to provide a long oxide superconducting cable conductor having flexibility as well as excellent superconductivity. In the present invention, an eddy current or a coupling current transferred between and flowing across the superconducting tapes is suppressed by  
10 the second or subsequent layer of tube-shaped superconductive wires which is provided according to one embodiment of the present invention. The present invention provides a practical AC superconducting cable conductor.

Advantageously the superconductor material is a granulated ceramic inserted into a  
15 silver tube which is then drawn to about 1 to about 2 mm. A number, depending on the desired capacity of the final cable, of these small drawn tubes are then inserted into a silver tube which is drawn to the desired size for use. Optionally, such tube may first be cut into sections and then added to the second silver tube before drawing. This thin, silver, flat tape-shaped material is from about 80 to about 60 percent silver  
20 and about 20 to about 40 percent ceramic by weight, advantageously, about 65 percent silver and about 35 percent ceramic.

The present invention also relates to a novel process or method which produces polymeric tapes suitable for use in a cryogenically operated superconducting power  
25 cable and the tapes so produced. The processing includes biaxially orienting either a polyethylene, polypropylene, or polybutylene film which has a maximum dielectric constant of about 3.0 and embossing said film with a random pattern. The combination of low dielectric constant, biaxially oriented, embossed film yields a polymeric material which overcomes the problems of brittleness, crazing, and  
30 excessive shrinkage which renders polymeric materials produced by known processes unusable in cryogenically operated power cable systems. In addition, the embossing of the film permits the relatively free flow of dielectric fluid within the cable.

35 The polyolefin sheet stock is biaxially oriented before use in the cable of the present invention. This involves stretching the sheet to a draw ratio of between about 5 to 1

- 5 and about 10 to 1 in the length direction and also orienting the sheet across their width.

10 The sheet, and tapes obtained therefrom which results from processing polyolefin stock to appropriate draw ratios has numerous qualities which make it superior for cable manufacture. To reduce the tape's tendency to fibrillate, to split over its entire length along a single tear, further processing is desirable. This processing involves a biaxial orientation in the direction across the sheet. This orients the sheet to a ratio of up to about 50% in the cross-sheet direction, and produces tape which is sufficiently biaxially oriented to satisfactorily limit the tendency to fibrillate.

15

The polyethylene, polypropylene and polybutylene tapes produced from the processing noted above are embossed with a particular pattern under specific conditions to assure proper cable impregnation and heat transfer. The embossing pattern consists of random or irregular channels, primarily directed in the cross machine direction. The tapes are cut from or otherwise obtained from the oriented  
20 sheet and may be used as single or multiple layer or laminate tapes.

At the same time the pattern, while it may permit some impregnant flow in both the machine and cross-tape direction, favors cross-tape flow and flow between butt gaps  
25 because such flow enhances impregnation from layer to layer and encourages heat transfer by convection. The cable itself is constructed of multiple layers of polyolefin tape, either polyethylene, polybutylene or polypropylene. To facilitate cable bending, different widths of polyolefin tape may be used in the layers. The sizes may progress to larger widths with increased distance from the conductor of the cable.

30

The polyethylene, polypropylene, or polybutylene film of the present invention has a dielectric constant no greater than about 3.0, with about 2.3 being the preferred maximum. The first processing step consists of biaxial orientation, or drawing, advantageously at a ratio of from about 5 :1 to about 6:1 in the machine direction and  
35 up to about 2:1 in the cross machine direction. Following orientation, the oriented tape is embossed at a temperature of from about 80°C to about 140°C, which produces

- 5 on the tape a pattern consisting of irregular or random channels primarily directed in the cross machine direction.

Polymeric tapes which have not undergone the novel processing steps described above have several inherent problems which make them unusable in cryogenically  
10 operated superconducting power cable systems. For example, in a liquid nitrogen environment at 77°K, most polymeric tapes become glass hard. This will lead to either tensile failure due to thermal contraction exceeding the inherent elongation or to simple disintegration of the tape. Another problem is crazing in liquid nitrogen. Liquid nitrogen, with a boiling point of 77°K, is known to be a powerful crazing agent  
15 for polymers. Crazing usually leads to stress cracking and ultimately fracture of the tape. The biaxial orientation process described above overcomes these problems of brittleness, excessive shrinkage, and crazing.

Many polymers exhibit two distinct modes of yielding. One type of yielding involves  
20 an applied shear stress, although the yield phenomenon itself is influenced by the normal stress component acting on the yield plane. The second type of yielding involves yielding under the influence of the largest principal stress. This type of yielding is frequently referred to as crazing, or normal stress yielding. Crazing can be induced by stress or by combined stress and solvent action. It shows generally similar  
25 features in all polymers in which it has been observed. Crazing appears to the eye to be a fine, microscopic network of cracks almost always advancing in a direction at right angles to the maximum principal stress. Crazing generally originates on the surface at points of local stress concentration. In a static type of test, it appears that for crazing to occur the stress or strain must reach some critical value. However,  
30 crazing can occur at relatively low stress levels under long-time loading.

It is known from extensive electron microscopic examination of crazed areas that molecular chain orientation has occurred in the crazed regions and that oriented fibrils extend across the craze surfaces.

35



5 To aid in the construction of the cable the otherwise highly transparent polyolefin insulating tape advantageously is produced with coloring added. This technique adds significantly to the ability to make a useable cable, because the operator must properly index each subsequent spiral layer of tape with the immediate previous layer. When taping with the typical extremely clear and transparent polyethylene, 10 polybutylene or polypropylene tape, the operator is unable to distinguish the butt gaps of the immediate previous layer from other butt gaps as far as eight or ten tape layers beneath. The addition of selected color dyes in specific quantities adds enough color to the tape to permit the operator to easily distinguish the edges, the butt gaps, of the immediate previous layer of tape from those of the earlier layers because the darkness 15 of the color increases significantly with each layer. This coloring agent is selected so as to minimize any increase in dissipation factor of the original material.

The width of the tapes may vary; narrow near the conductor and wider at the outside. The direction of lay may also be reversed at a certain radial thickness, a factor which 20 depends on the design of the taping machine.

The dielectric tapes may be wound in overlapping spiral layers so that each butt gap between spirals of the same layer is offset from the butt gap of the layer below. This construction is facilitated by the production of the insulating tape containing color. 25

Polyolefin tapes such as polyethylene, polybutylene and polypropylene, when highly oriented as required for the present invention, are transparent. This clarity becomes a disadvantage when the butt gaps of many layers show through to the surface of, the cable very clearly. The operator then has difficulty distinguishing the butt gap of the 30 immediate previous layer, from which each new butt gap must be offset, from other butt gaps deeper within the cable.

The tape of the present invention therefore has a color component added to it so that the deeper a layer is within the cable, the darker it appears. Organic dyes may be used 35 to produce this color because these organic compounds, unlike inorganic metal salts, have less detrimental effect on the loss tangent and permittivity of the tape.

5

Since a balance between the needed color and effects on the electrical characteristics must be struck, organic dyes are added in the proportions ranging between 100 to 1000 parts per million.

10 This results in a reduction in the light transmission of the tape to 10 to 50 percent of the original transmission. When the tape is used on a cable this reduces the visibility to one to four layers, whereas without color, butt gaps as deep as eight to ten layers within the insulation are, still visible.

15 Orientation is accomplished in the machine direction by stretching or tentering of the sheet to produce a thickness reduction ratio of between 5 to 1 and 10 to 1.

The thickness reduction ratio is in fact a measurement of the linear sheet orientation and is an indication of the changing tensile characteristics of the polymer. The  
20 process is advantageously performed at temperatures of between about 80°C and about 140°C.

The sheet is also processed to orient it in the cross-sheet direction to a reduction ratio of up to 50%. This is necessary because without such processing polymers tend to  
25 fibrillate, that is, to separate into individual fibers across their width and cause the tape to split lengthwise.

Polyolefin tapes resulting from the processing specified above, however, have a tensile modulus of at least 250,000 psi in the length (machine) direction, and meet all  
30 the criteria required for cable manufacture.

The tensile strength attained by the tapes through the processing is not only an indication of the resistance to deterioration, but also a necessity for the use on cable  
taping machines. Tapes processed as described above can therefore be used on  
35 conventional cable making machines with tensions great enough to construct a satisfactory tightly wound cable.

5 Before final construction into a cable, the polyolefin tape is embossed to furnish spacing between the tape layers which will facilitate relatively free flow of impregnants within the cable to enhance heat transfer.

These goals are accomplished by a specific embossing technique. The tape is  
10 embossed advantageously by rollers. A typical pattern of embossing is shown in FIG. 4 which is a top view of a small section of tape 60 with valleys 61 in the pattern shown as dark lines.

The embossing pattern is characterized as irregular and preferentially permitting  
15 cross-tape flow of impregnant as opposed to flow along the length of the tape. The pattern of irregular valleys running essentially across the tape width as seen in FIG. 4 meets these criteria and, unlike a pattern of regular grooves or channels, it can not interlock adjacent tape layers. Non-uniform and irregular patterns therefore assure that the various tape layers can move small distances relative to each other and yield  
20 the degree of flexibility required to manufacture and install the cable.

The cross-flow favoring pattern provides heat transfer and impregnation capabilities for the cable. Although it is well understood that polymers are not permeable, the mechanism available for impregnation and heat transfer in the present cable does not  
25 depend upon the permeability of the material itself.

The embossed pattern is such that it can increase the effective tape thickness, that is, the peak to peak thickness may be twice the distance of the original tape thickness. The tape is then compressed during winding. Embossing is accomplished by rollers  
30 which cause a depression in one surface of the tape and a protrusion in the other surface. Once wound into a cable, these surface irregularities separate the tape layers; but since the pattern favors across-the-tape flow, impregnants need only flow, at the most, one-half the width of the tape to or from a butt gap where it can then progress to the next space between the tapes. This results in a relatively short path from the  
35 outside of the cable to the conductor.

- 5 Two typical patterns of embossing are: a coarse pattern with a typical 0.1mm mid-height width of the valleys and a typical 0.2mm spacing between adjacent peaks; and a fine pattern with typical 0.025mm mid-height valley widths and typical 0.05mm spacing between peaks.

10 The availability of embossing patterns ranging from coarse to fine allows the cable designer to strike a compromise between heat transfer and operating stress. The coarse pattern provides the best heat transfer with some reduction in operating voltage stress compared to the fine pattern and vice versa.

The present invention also includes cable and terminations and test procedures  
15 therefor. The cable test facility consists of a 5-m HTS cable between two terminations, and associated support systems such as ac and dc power supplies, cryogenic cooling skid and the data acquisition system. The facility cryogenic system uses a subcooler to provide up to 1 kW cooling for the cables and terminations. Boiling of the liquid nitrogen in the subcooler accommodates the total facility heat  
20 load. The shell side of the subcooler can be pumped by a vacuum pump to maintain the nitrogen bath temperature in the range of 70 to 77 K, although much of the test program was carried out with no subcooling, with the average cable temperature in the range 79-81 K. The system cycle is an open one where the exhaust from the shell side of the subcooler is ultimately vented to the atmosphere. The process cooling fluid  
25 (nitrogen at <10 bar) flows through the tube side of the subcooler and is routed to the cable supply manifold. Nitrogen leaving the cable/terminations flows to the inlet of the LN circulation pump, which provides the pressure head for the closed loop flow of the pressurized nitrogen.

30 Electrical and cryogenic data are taken by dedicated sensors scanned by three ten-channel multimeters connected to a personal computer (PC)-based, data acquisition system using the LabVIEW program. These diagnostics allow measurement of the dc V-I characteristics and the ac losses of the cable, dielectric integrity via a partial discharge measurement, and cryogenic performance at rated voltage (7.2 kV ac rms)  
35 and current (1250 A). A high-voltage power supply is available (rated at 1 A at 18 kV) to test the cable at a peak voltage level of 2.5 times the operating voltage. The

- 5 dedicated impulse power supply was upgraded from 100 kV to 200 kV and a 25 kA pulsed power supply installed to simulate cable overcurrents due to system faults.

Two termination concepts have been developed. The majority of the cable test program was carried out with a vacuum termination concept that uses the vacuum for  
10 both electrical and thermal insulation. Each vacuum termination had two sets of feed-throughs, one set for the phase conductor and the other set for the HTS neutral conductor. Each set had a warm ceramic bushing making the transition from ambient (295 K, 1 atm) to vacuum (295 K) and the second ceramic bushing making the transition from vacuum to (~72–81 K) liquid nitrogen at <10 bar. These bushings are rated  
15 for full cable current and voltage. The two terminations are pumped through a common vacuum header by a mechanical/turbomolecular pumping station; typical vacuum is in the  $10^{-5}$  to  $10^{-4}$  torr range, which provides sufficient thermal insulation when combined with multi-layer superinsulation. There were concerns about the reliability during cooldowns and in service for long time periods. A slight leak in  
20 either cold bushing due to thermal or electro-mechanical stresses would degrade the vacuum in the termination. Only a small amount of liquid nitrogen leakage is required to put the vacuum at the Paschen minimum for nitrogen gas, which breaks down at ~250 V, a much lower level than the operating voltage. Therefore, an alternate termination embodiment was developed that operates with pressurized liquid and  
25 gaseous nitrogen. It is shown in Fig. 5.

Like its vacuum predecessor, it is designed for 18 kV ac withstand and 110 kV BIL. It is, however, more compact than the vacuum termination as shown in Fig. 6. The basic concept is: there are no cold phase or shield bushings. Each termination has two  
30 conventional warm bushings with no significant thermal stresses. Between these warm bushings and the ends of the HTS cable is a concentric arrangement of copper pipes designed to minimize the axial heat conduction at the operating cable current. Non-metallic cylinders are used for electrical insulation between the phase and neutral copper pipes. The dynamic vacuum system is eliminated and what remains is a  
35 normal static vacuum system with multi-layer superinsulation to reduce the radial heat loss. The entire termination is at the cryogenic system pressure and there is a natural

5 thermal transition from liquid to gas along the copper conductor pipes. If there is a leak the internal pressure slowly reduces to atmospheric nitrogen pressure (which can withstand 30 kV/cm) and the system is designed to avoid breakdown in such an event. This termination design is more operationally efficient in that vacuum leak testing and pumpdown are eliminated.

10

In an extended test program in pressurized termination successfully completed the following tests:

- extended operation at design current (1250 A ac rms) and voltage (7.2 kV phase-to-ground)
- 15 • ac withstand test to 18 kV for 30 minutes with no breakdown
- impulse testing to 90 kV (see discussion below on cable testing)
- measurement of termination heat loads

The heat loads were gradually reduced through a series of design improvements as shown in Fig. 7, with the best performance on the 30-m cable terminations.

Six of these pressurized terminations in the 3-phase, 30-m HTS cable were tested. The heat load on the pressurized terminations installed on the 30-m cable with an ac current of 600 A is about 230 W per termination. Each termination has two  
25 conduction-cooled copper leads (pipes) with a theoretical minimum heat load of 44 W/kA each.

The single-phase, 5-m cables tested had inner cable conductor consisting of four layers of helically wound, Bi-2223/Ag tapes. Four layers were chosen to provide  
30 enough capability for the design current of 1250 A. The tapes were machine wound at a 30° angle on a stainless steel former with an outer diameter of 38 mm. Cryoflex™ dielectric tape was wrapped between the inner and outer HTS conductors. The outer HTS cable conductor is similar to the inner conductor and provides shielding of the currents flowing on the inner conductor and thus eliminates magnetic fields or eddy  
35 currents in the external structure. The outer HTS cable conductor is at ground potential.

5

The 5-m cable test results included a successful overcurrent test up to 12.8 kA for a 2-s pulse length (see Fig. 8). This is over ten times the design current and simulates a short circuit on the load side.

- 10 The cable was also tested for basic impulse loading (BIL) to simulate surges such as lightning strikes. The requirement for 15 kV class distribution cables is 110 kV BIL, with the pulse rising to this maximum in 1.2  $\mu$ s. The HTS cables and terminations withstood a BIL up to about 90 kV (see Fig. 9) and would breakdown above that value. When the test voltage was lowered to below 90 kV, the system again  
15 withstood the test pulse.

- A 5-m cable was removed from the test facility and bent in a wooden fixture of the same diameter (2.44 m) as a cable shipping spool. It was bent in one direction and the reverse direction over four cycles. Cable testing before and after bending indicated no  
20 damage to the dielectric system as ac withstand and impulse loading were unchanged from previous tests. The cable critical current was reduced by about 15 % after bending (see Fig. 10).

- A cold dielectric, tri-axial cable was also developed and tested. A ~1.5 m long cable  
25 was fabricated. This configuration is more compact than three separate single-phase cables and the amount of HTS tape is reduced significantly as a balanced load would produce no net induced current outside the three concentric phase layers. The cable cross-section is shown in Fig. 11, indicating the relative size of a single phase and a tri-axial cable. The liquid nitrogen flow cross-sectional areas are about the same but  
30 the dielectric is somewhat thicker for the tri-axial cable due to the higher phase-to-phase voltage between the HTS conductors relative to the phase-to-ground voltage in a co-axial single-phase cable.

- Superconducting cable for ac yields potential low-loss transmission capability. There  
35 are known superconducting cables for this application, but the construction is complex, so the manufacture of the cables is very expensive. The phase conductors are manufactured of metallic superconducting material. This necessitates separate

5 cooling for each phase. The space within the phase conductors is thus used as a channel for the cooling material whereby closed-loop liquid nitrogen or helium is used for the cooling system.

One embodiment of the present invention is a superconducting cable that is more  
10 compact, requires less material, and whose cooling mechanism is smaller than known superconducting cables.

The present inventive superconducting cable is constructed so that only a single neutral conductor is required for the three phase conductors (R, S, T). Additionally,  
15 the phase conductors, the neutral conductor, and the cooling channels are concentrically arranged around one another resulting in a very compact construction. The cooling of the cable takes place with liquid nitrogen. An electrical insulation manufactured of polyethylene or polypropylene is placed between the phase conductors (R, S, T) as well as the neutral conductor. The cable restricts outward  
20 temperature loss through vacuum and/or insulation. The coolant circulates out in the core of the cable and back in an annular channel that is directly connected to the vacuum/insulation.

Figure 27 illustrates the superconducting cable (1) of the present invention in cross-  
25 section. The core of the cable is formed around a channel (2) with a diameter of from about 50 to about 200 mm through which the coolant is conducted. Other diameters can likewise be selected. Channel (2) defines the boundary of first phase conductor (R). The sheath of channel (2) is manufactured of a superconducting material. Preferably the phase conductor (R) is manufactured of superconducting tapes. The  
30 superconducting tapes are sleeves of silver filled with a high temperature superconductor ceramic material. Subsequently the sleeves are rolled into surfaced tapes. These tapes are then wrapped on a mandrel whereupon the conductor (R) is built. The thickness of conductor (R) preferably is from about 0.1 to about 10 mm. An electrical insulation (3) is placed on the first phase conductor. This is  
35 advantageously made of polyethylene or polypropylene. The phase conductor (R) tapes are wound with these materials until the insulation (3) reached the desired



5 thickness. The thickness of the insulation is preferably from about 10 to about 50 mm. The second phase conductor (S) is applied over insulation (3). This is again manufactured with tapes of superconducting material which are in turn wound about the insulation (3). The phase conductor (S) achieves the same capacity as the phase conductor (R). Applied to the phase conductor (S) is a subsequent insulation (4).  
10 This is manufactured in the same manner and capacity as insulation (3). The third phase conductor (T), which is manufactured in the same manner and capacity as the phase conductors (R) and (S) is applied over the insulation (4). A further insulation (5) that is manufactured in the same manner as the insulations (3) and (4) is applied over the phase conductor (T). Optionally the thickness of the insulation (5) may be  
15 less than the thickness of the insulations (3) and (4). The boundary of the neutral conductor (6) is outwards of the insulation (5). This neutral conductor (6) has, under symmetric load, only a small current to carry, and can therefore be manufactured of customary conducting material, preferably copper. The thickness may only be a few mm. The return conductor serves simultaneously as a border for the closed-ring  
20 cooling channel (7) through which the circulating liquid nitrogen is conducted. The diameter of the cooling channel (7) preferably is from about 150 to about 500 mm. A vacuum or super-insulation is outwards of the cooling channel (7). This defines an inner boundary surface (8I) and an outer boundary surface (8A). Between both boundary surfaces an annular space is formed, which is evacuated or filled with a  
25 super insulation.

The cable of the present invention was cooled down to about 81 K with liquid nitrogen at about 4.7-atm pressure and a flow rate of about 0.19 l/s (3 gpm). Short current pulses much larger than the critical current,  $I_c$  (about 910 A) of the cable were  
30 applied to the cable to simulate fault currents in case of an in-service short circuit. The voltages across the phase conductor and the joint, the current and voltage of the shield conductor, and the temperature and pressure of the coolant during the pulse and for a period after the pulse were monitored. Shots were made first with a 1-s pulse at increasingly higher current from 4.8 to 12.8 kA. The pulse length was then increased  
35 to 2 s and again up to 12.8-kA current pulses were applied. The pulse length was

5 shortened to 0.5 s and a current of 15.3 kA was applied. Finally, the pulse length was lengthened to 5 s and a current of 6.8-kA was applied.

Fig. 12 shows the current and voltage traces of the cable on a typical shot. A fault-current pulse of about 12.8 kA was programmed to apply to the cable for 2 s. As soon  
10 as the current reached 12.8 kA, a voltage (V-cable) of about 3.2 V was developed across the cable. This and the voltage drops along the terminations and external power supply cables had apparently exceeded the power supply limit (12 V) and caused the current to drop. By the end of the 2-s pulse, the current was lowered to about 6.9 kA. However, the cable voltage continued to rise  
15 to over 5 V, indicating heating in the conductor. On the other hand, the cable-to-connector joint voltage (V-joint) was lowered from about 0.3 to 0.17 V – in the same proportion as the current drop.

The cable voltage rise indicated a temperature rise had occurred. The measured  
20 voltage was divided by the corresponding current to get the resistance response of the cable. The result is shown in Fig. 13. It is seen that at the beginning of the 12.8-kA pulse, the cable resistance went to 0.25 m $\Omega$  (as compared to 0.54  $\mu\Omega$  at critical current) and increased to 0.72 m $\Omega$  by the end of the 2-s pulse. (The discontinuity at the beginning and end of the current pulse was due to dividing the cable voltages by  
25 the near zero currents.) Based on the silver resistivity change as a function of temperature, the above resistance change of the cable indicated that the HTS conductor had heated to about 170 K by the end of the pulse. Although the cable voltage nearly disappeared after the current pulse in Fig. 12, its resistance in Fig. 13 showed a relatively slow cool down to about 0.1 m $\Omega$  seven seconds later.

30

In the construction of the cable, the HTS tapes are separated from the coolant on the ID with bedding tapes and a corrugated stainless tube and on the OD with layers of Cryoflex dielectric tapes. Thus, cooling of the HTS tapes is essentially by conduction only. The heating of the HTS tapes during the fault-current pulses can be  
35 approximated as adiabatic. Integrating the product of current and voltage (the power) over the pulse in Fig. 12, the total energy generated in the conductor in this shot was

5 found to be about 80 kJ. Using the silver specific heat integral, it was estimated the conductor would heat up to about 175 K adiabatically. Figure 13 indicates the joint resistance remained at 24  $\mu\Omega$  throughout the shot. There was no noticeable temperature rise on the joint because of its better cooling condition (with direct contact with  $\text{LN}_2$ ).

10

The fact that in response to an over-current, the cable resistance becomes much higher than its value at  $I_c$  means that the HTS cable possesses an intrinsic current limitation function. Determining the extent of the cable resistance rise during an over-current indicates the extent of the current limitation offered by the cable. From the moments  
15 the different pulsed currents reached their peaks, the cable resistance at all 15 over-current shots was determined. The result is shown in Fig. 14 as a function of current. The 5-m cable resistance increased rapidly from 0.54  $\mu\Omega$  at  $I_c$  to 0.31 m $\Omega$  at 15.3 kA — nearly 600 times higher.

20

The dc V-I curve (see in Fig. 18) shows that above  $I_c$  the voltage of the present superconductor increases in proportion to  $I$  to the 3.8<sup>th</sup> power (the  $n$ -value). Thus, the resistance of the superconductor at an over-current,  $I$  can be scaled from its value of 0.54  $\mu\Omega$  at  $I_c$  by a factor of  $(I/I_c)^{2.8}$ . In addition to the superconductor, the present HTS tape contains 70% of silver in the composite. Using a resistivity of 0.3  $\mu\Omega$ -cm,  
25 the resistance of the silver matrix in the cable is estimated to be about 0.25 m $\Omega$  at liquid nitrogen temperature. The cable resistance in the over-current regime was then calculated by paralleling the scaled HTS resistance with the silver resistance. The result is shown as the calculated curve in Fig. 14. It is seen that the measured data follows the calculated curve very well — proving the power-law scaling of the HTS  
30 resistance above  $I_c$  is appropriate.

This indicates that the HTS in the present cable shared the fault current equally with the silver matrix at 8.1 kA — about 9 times the critical current. Below this value the current flows mostly in the superconductor, above this value more and more current  
35 flows in the silver matrix. At 15 kA, the HTS can carry only 15 % of the fault

5 current. Above 10 kA the measured data lays above the calculated curve, indicating tape heating before the fault current reached its peak value.

Because of the high voltage drop developed across the cable during a fault over-current, the power is high and the total energy dissipation can be significant when the pulse length is long. When this energy is dumped into the coolant, the temperature and the resulting pressure rise may upset the cooling system. The shot shown in Fig. 12 produced the highest energy dissipation of all the shots. In Fig. 15, the responses of the temperature sensors are shown for this shot. The sensor "T-out" is located near the coolant outlet of the cable inside the termination, and "T-far" is located at the cable-side of the far-end termination. Neither of these sensors in the flowing coolant showed any temperature rise during or after the current pulse. Only sensor "T-bus" which is located at the bus-side of the far-end termination showed a temperature rise of about 5 K, 3 s after the pulse. This sensor was cooled by stagnant gas, and was at a higher temperature of about 96 K.

20

The total energy produced in the cable in this shot was about 80 kJ. If half of this energy were dumped instantaneously into the liquid nitrogen in the inner pipe (the former) of the cable the temperature would rise by about 5 K. No such temperature rise was observed. The phase conductor was not cooled directly by the coolant, and it took tens of seconds for the conductor to cool (and thus to release heat to the coolant). The liquid nitrogen flow rate of about 0.2 m/s inside the pipe replenished the coolant fast enough to prevent any measurable temperature rise in the coolant.

Fig. 16 shows the corresponding pressure changes in the same shot. Contrary to the temperature response, it is seen that both the inlet and outlet pressure start to rise 1 s into the pulse and reached a peak value of about 0.34 atm (5 psi) at 1 s after the pulse. Both pressure taps were meters away from coolant inlet and outlet of the cable. The pressure wave reached them in a fraction of a second (with the speed of sound in liquid nitrogen). Since no temperature rise in the coolant was observed, the pressure rises resulted from transient heating in the terminations.

35

- 5 Over the one-hour span of the 15 simulated fault-current shots, the accumulated temperature rise of the cable outlet coolant was about 1 K, and there were no significant system pressure changes. Repeated fault-currents that are separated minutes apart would not upset the present HTS cable nor the cryogenic system.
- 10 The voltage and current induced in the shield loop by the fault current in the phase conductor are another concern. In the experiment, the two ends of the superconducting shield were tied together with copper cable and a current shunt to monitor the induced current. Fig. 17A shows the induced current in the shield loop for the 12.8-kA, 2-s fault-current shot. Only about 350 A and 120 A of transient
- 15 currents were induced in the shield at the rise and fall of the phase conductor over-current. Part of the reason for these low values is due to the relatively long rise and fall time (of about 300 ms) of the over-current provided by the present power supply. If a fault current would rise faster, the induced transient in the shield would be higher. During the 2 s of slow decrease of over-current, there was no measurable induced
- 20 current in the shield.

Fig. 17B shows that the maximum voltage developed over the shield conductor was less than 0.35 mV. Since this voltage is lower than the critical-current voltage of 0.5 mV for this cable and the induced transient current was lower than the critical current,

25 therefore the shield conductor stayed superconducting during the fault-current pulses.

To determine if there was any significant degradation of the cable from the simulated fault current shots, the dc V-I curve of the cable was measured after the present fault

30 current tests. Fig. 18 shows the present V-I curve of the cable as compared to a measurement made a year earlier. There is no difference in the two V-I curves. Between these two dc V-I measurements, the cable was subjected to high-voltage withstand tests to 18 kV, impulse tests to 90 kV, long duration (72 hr) testing at the design current and voltage, and tens of cool-down and warm-up cycles. The cable

35 showed no degradation in its dc characteristics throughout these tests. At the criterion of  $1 \mu\text{V}/\text{cm}$ , the critical current of the cable remained at about 910 A.

- 5 HTS cables are being proposed for retrofitting existing underground cables. In common underground cable installations, the three separate phases are installed in separate ducts. It is assumed there is a refrigeration unit supplying subcooled liquid nitrogen, at only one end of the cable. The HTS cable configuration, shown in Fig. 19, illustrates a single cryostat counterflow cooling arrangement for the HTS cable. The
- 10 HTS cable former and cryostat walls are typically taken to be flexible, corrugated stainless steel tubing. The HTS cable of the present invention is a cold dielectric configuration and requires a superconducting shield layer, separated by a dielectric material from the main conductor. The shield carries the same current as the main conductor.
- 15 In the counterflow cooling arrangement the liquid nitrogen flows through the HTS cable former providing cooling to the terminations as well as the cable and returns in the annulus between the outside of the cable and the inner cryostat wall. In the parallel flow arrangement, liquid nitrogen flows in the same direction through the
- 20 cable former and the annulus. The liquid nitrogen is returned either through a separate vacuum jacketed duct. The single cryostat for the return flow is taken to be the same as the cable cryostat. The dimensions used in this study for these two cases are given in Table 5.

25

TABLE 5  
Cryostat Dimensions

Nominal Dimension	Counterflow	Parallel Flow
Former diameter (mm)	38	38
Cable diameter (mm)	65	65
Cryostat inner diameter (mm)	75	75
Cryostat outer diameter (mm)	125	125
Return cryostat inner diameter (mm)	-	75
Return cryostat outer diameter (mm)	-	125

- It is assumed that two phase flow of liquid nitrogen is not permitted in the HTS cable
- 30 power transmission system. First, two phase flow pressure drops are higher than for single phase flow. In addition, gas bubbles in the dielectric could decrease the cable electrical insulation levels.

- 5 The ac loss and thermal analysis of HTS power transmission cable systems is accomplished by performing an energy balance of the cable system. For the HTS cable, the one-dimensional energy balance equation can be written as:

$$\rho c \frac{\partial T_{HTS}}{\partial \tau} = \frac{\partial}{\partial x} \left( k A_{HTS} \frac{\partial T_{HTS}}{\partial x} \right) + Q'_{AC} - \sum_i Q'_{conv,i} \quad (1)$$

10

where  $\rho$  is the density,  $C$  is the heat capacity,  $z$  is the coordinate direction along the cable axis,  $k$  is the thermal conductivity, and  $A$  is the cable cross-sectional area.

- The HTS cable energy balance includes a convection heat transfer terms  $Q'_{conv,i}$ , include convection to the liquid nitrogen flow in the former and also in the annular region between the cable and the cryostat inner pipe. The product of the thermal conductivity and the cross sectional area of the cable,  $kA_{HTS}$ , are constant for this work and is equal to 0.16 Watt-meter per Kelvin. Additional energy balance equations are needed for the liquid streams and are given by:

$$20 \quad \rho_{vi} c_{p,vi} \frac{\partial T_{vi}}{\partial \tau} = \dot{m} \frac{\partial h_{vi}}{\partial x} + \sum_i Q'_{conv,i} \quad (2)$$

- where  $i$  represents each liquid nitrogen stream (former flow, annulus flow, and return flow as applicable). The convection heat transfer to the inner flow is solely with the inside of the HTS cable former. The outer nitrogen flow exchanges heat convectively with the outside of the HTS cable and with the inside of the double walled flexible cryostat.

- 30 The convective heat transfer coefficients are calculated using:

$$N_{Nu} = \frac{C_h d_{hyd}}{k_{LN2}} = 0.023 N_{Re}^{0.8} N_{Pr}^{0.3} \quad (3)$$

5 where  $N_{Nu}$  is the nusselt number,  $C_h$  is the heat transfer coefficient,  $k_{LN2}$  is the thermal conductivity of the liquid nitrogen,  $N_{Re}$  is the Reynolds number, and  $N_{Pr}$  is the Prandtl number.

The equations are cast into a finite difference form and numerically integrated in time  
10 until a steady state is reached. After the determination of the temperature profiles, the pressure drop can be approximated by integrating the following equation over the flow path length:

$$15 \quad dP = \rho V dV + f \frac{\rho V^2}{2} \frac{dx}{D} \quad (4)$$

20 where  $V$  is the liquid velocity and  $f$  is the friction factor.

In a rigorous treatment, the thermal-hydraulic solutions should be coupled, but it is assumed that compressibility effects and density variations are small for liquid nitrogen under the conditions considered in this work. Therefore the temperature and pressure profile solutions were performed separately. The friction factor for cryogenic  
25 liquid flow in corrugated bellows has been suggested to be four times that for a smooth pipe. In the cases presented here, the Reynolds numbers are in the range of  $10^5$  to  $10^6$ , and a constant friction factor  $f=0.07$  was used. The pressure drop across the terminations is assumed to be small and is neglected.

30 The HTS cable cryostat is taken to be a flexible double wall construction with the dimensions listed in Table 5. The sink temperature,  $T_\infty = 300$  K. Typical commercially available vacuum insulated flexible cryostats have an effective, on actual field installation thermal conductivity,  $k_{eff}=0.0008$  Watts per meter per Kelvin. The local heat transfer per unit length can be calculated and depends on the local  
35 liquid nitrogen temperature  $T_{vi}(x)$ , and the cryostat inner and outer tube diameters  $D_{ci}$  and  $D_{co}$ . The temperature difference driving this heat transfer term is typically over 220 K for the outer cryostat.



5

$$Q'_{cstat,i} = \frac{2\pi k_{eff}(T_{\infty} - T_{v,i}(x))}{\ln(D_{co} / D_{ci})} \quad (5)$$

10 The critical current was scaled from earlier measurements on the 5-meter system. Using the measured linear fit in temperature, the critical current can be scaled with temperature using a reference value of 3000 A at 77K by the following:

$$I_c(T) = 6188.2 - 41.405T \quad (6)$$

15

The ac loss,  $P_{AC}$  in watts per meter, is computed using the monoblock model.

$$P_{AC} = \frac{\mu_0 f I_c^2}{2\pi h^2} \{ (2 - Fh)Fh + 2(1 - Fh)\ln(1 - Fh) \} \quad (7)$$

20

where  $F = I_p / I_c$ , the ratio between the peak current in the ac cycle and the critical current of the superconductor,  $f$  is the frequency, and  $h = (D_o^2 - D_i^2) / D_o^2$ . This study will show results for operating currents of 1500 A<sub>rms</sub> and 2000 A<sub>rms</sub>.

25

The dielectric loss depends on the design voltage of the cable. A nominal value of 0.05 Watts per meter was assumed and is consistent with earlier work.

30 The model was compared to measurements on a 5-meter HTS cable system. A comparison of the measured temperatures for operation are given in Fig. 20. In this case, the 5-meter HTS cable was cooled with a flow of 210 grams per second of liquid nitrogen supplied at a temperature and pressure of 79.2 K and 5.4 bar. The applied current to the cable was 1250 A<sub>rms</sub>. The measurements qualitatively agree with the calculation. The discrepancies in temperatures are primarily due to the use of a  
35 simplified thermal model for the terminations, which for short cables, is the dominant system heat load. The terminations had vacuum thermal and electrical insulation. Each termination contained two optimized current leads to carry in excess of the rated

5 current of 1250 A<sub>rms</sub>. The termination heat load is about 300 Watts for each end. While there is some variation in the termination heat load due to the level of operating current, the difference is considered to be small, particularly for long cables, and is neglected.

10

For a HTS power transmission system, the termination heat loads are constant, and independent of the length of the transmission cable system. The ac loss and thermal load through the cryostat depend on the length of the HTS transmission cable system, the cooling flow configuration, the supply temperature and flow rate.

15

Constant liquid nitrogen conditions, a pressure of 10 Bar and a temperature of 67 K, were used. The properties of liquid nitrogen were obtained using GASPAK. This pressure is well within the capabilities of commercially available flexible cryostats, and the temperature is typical for a subcooler refrigeration unit. The triple point of  
20 nitrogen is about 63.2 K, so lower temperatures, say 65 K, could be achieved using closed cycle refrigeration systems.

25

The critical current and temperature profiles are shown for the two long length cases at flows of 1000 grams per second per phase and both cooling arrangements in Fig. 21 and Fig. 22. Temperature limits are clearly shown to exist in the counterflow flow case. In this case, the bottom temperature line is the former flow temperature, the center line is the HTS cable temperature, and the top line is the annular return flow temperature. The pressure drop for the 500 meter long counterflow case, shown in Fig. 23 is 4.7 bar. Increasing the flow to reduce the cable temperature would increase  
30 the pressure drop, which is already high, and introduce the possibility of boiling in the cable. In both cooling arrangements the higher current cases produced higher temperatures, reducing the HTS cable critical current, and increasing ac loss.

35

The refrigeration loads at 67 K are shown for both cooling arrangements as a function of length in Fig. 23 and Fig. 24. These results show that running the cable at the lower current results in a significant drop in the ac loss but that the cryostat loss does not depend at all on the current level in the cable.

5

Many crucial factors in a HTS power transmission cable system depend on the cooling flowrate. A 250 meter counterflow case and a 1000 meter parallel flow case were analyzed to determine the maximum cable temperatures and pressure drops at a current of 2000 A<sub>rms</sub> at different flowrates. These results are presented in Figs. 25 and 26.

In both arrangements, higher temperatures are reached in the cable at lower flow rates. In the counterflow case, the system temperature, at which the liquid nitrogen is returned to the refrigerator, is at a lower temperature than the cable maximum. The opposite is true for the parallel flow cooling arrangement. For low flows, the counterflow cooled cable maximum temperatures are high enough to significantly reduce the superconducting properties of the cable. Increasing the flow reduces the maximum temperature at the expense of higher pressure drop. This is not the case for these flowrates in parallel flow even at a length of 2000 meters.

20

The HTS cable configuration, shown in Fig. 19, illustrates a single cryostat, counterflow-cooling arrangement for the HTS cable. The HTS cable former is a flexible, corrugated stainless steel tube. The HTS cable is a cold dielectric configuration and requires a superconducting shield layer, separated by a dielectric material from the main conductor. The shield is designed to carry the same current as the main conductor.

The features of the coaxial design are 1) image current in shield layer reduced external magnetic field and eddy currents in cryostat and ducts, 2) both the HTS conductor and dielectric are wrapped from tapes, 3) cryogenic dielectric reduces size and increases current-carrying capacity and 4) flexible cable to allow reeling.

30-m HTS cables were made using specially designed machinery to wrap the superconducting tapes onto the former. After the first two cables were wound including main conductor, cryogenic dielectric and shield, they were installed in their cryostats. Special end caps were fabricated for the cryostats to allow cooling of the

5 cables with liquid nitrogen at atmospheric pressure. Temporary voltage taps were installed on the ends of the main and shield conductors to allow measuring the critical current of just the superconductor. Fig. 28 shows the dc V-I curve of the main conductor for phase 2 of the 30-m HTS cable. A critical current,  $I_c$ , of 2980 A and an  $n$ -value of 9 was observed based upon the 1  $\mu\text{V}/\text{cm}$  criteria. The critical current of  
10 the phase 1 main conductor was more than 3000 A (the limit of the power supply). The critical current of one of the 5-m cables is also shown in Fig. 28 and is 1090 A with an  $n$ -value of 3. The design current of the 5-m and 30-m cables was 1250 A and the same number of layers and superconducting tapes were used in both the 5-m and 30-m cables. In the time that elapsed between procurement of the superconducting  
15 tapes for the 5-m and the 30-m cables, the tape performance improved dramatically. As a result, the 30-m cables while designed for a 1250 A rating, were actually ~3000 A conductors. With this extra margin, the superconductors contribute no resistance when operating at currents below about 1500 A, as shown in Fig. 28. At 2500 A, the voltage drop is 0.25  $\mu\text{V}/\text{cm}$  and the dc resistance is 0.01  $\mu\Omega/\text{m}$ . After measuring the  
20 critical currents, the temporary voltage taps were removed.

The HTS cable site is inside the dotted box in Fig. 29 and is part of the electric system delivering power to three manufacturing plants. A switching substation was constructed for the project, which allows either, or both the superconducting cable  
25 and the overhead line to serve the load. A control building houses the electrical control and protection panel for the superconducting cable, the cryogenic control system, and a conference room.

There are two 115-kV transmission lines providing service, to the general  
30 transmission substation. The transmission substation has a total capacity of 40 MVA with two 20 MVA matched, non-regulating, step-down transformers, 115 kV high side and 12.4 kV low side.

There are two 12.4 kV distribution feeders exiting the substation. Both feeders use  
35 1033.5 ACSR (aluminum conductor steel reinforced) which is a typical type of

- 5 conductor. The 12.4 kV protection system is a vacuum breaker with a reclosing relay set for three reclosures before lock-out. The symmetrical, 3-phase fault current is around 14,000 A at 12.4-kV. The 5-m superconducting cable has been successfully tested at fault currents above this level.
- 10 The HTS cable is cooled by circulating subcooled liquid nitrogen through the three cable phases. Based upon the 5-m cable testing program, the requirements for the 30-m cable cryogenic system were determined to be 3000 W heat load, 70-80 K operating temperature range, 1.3 l/s (21 gpm) flow rate and a maximum operating pressure of 10 bar. Two cryogenic refrigeration system designs were reviewed as
- 15 options — an open-loop boiling bath subcooler and a closed-cycle refrigerator. The open-loop system was selected because of the lower capital equipment costs. The operating costs of both approaches are comparable due to the higher efficiency obtained with large scale liquid nitrogen production plants over the smaller refrigeration unit that would have been used for the 30-m HTS cable system. For a
- 20 cable system with a much longer operational lifetime, a closed-loop refrigerator system, that included an open-loop nitrogen back-up system which would be used during maintenance on the main system, would be a better choice because it would not require frequent refilling of a bulk storage dewar.
- 25 The cryogenic system design consists of three main components — a liquid nitrogen storage tank, a cryogenic skid, and vacuum-jacketed piping.

The cryogenic skid contains a cold box which houses a subcooler, a phase separator, and two buffer volumes, under a common insulating vacuum. The cold box

30 components and associated piping are all wrapped with multi-layer thermal insulation to minimize the background thermal load. The cryogenic skid also contains three vacuum pumps used to lower the pressure on the subcooler bath and lower the operating temperature of the system. There are main and backup liquid nitrogen circulation pumps. The flow of liquid nitrogen follows a path through the system from

35 the circulation pump, through the subcooler, through the supply line to the cable, and returns via the return line to the phase separator at the inlet of the pump. The phase

5 separator is used during system start-up to prevent vapor from reaching the circulation pump. The subcooler is filled from the bulk storage tank. The subcooler boil off is vented to the atmosphere through the vacuum pumps, when operating below 80 K. The buffer tanks alternate in use, one is providing system pressurization while the other is filled and waiting.

10

The liquid nitrogen storage tank has a 40,000 liter capacity. The tank was mounted horizontally on concrete footings for a low profile. The tank level is monitored remotely using a telephone line and is filled by the liquid nitrogen supplier as needed.

15 Vacuum-jacketed piping connects the skid to the cable. There are three pipes - inlet, return and cooldown, connecting each of the three phases of the cable. With this arrangement, any combination of the three phases of the cable can be either in service, out of service or in a cooldown sequence.

20 A programmable logic controller system is used to operate the cryogenic system during normal operation. System cool down and restart are done manually due to the infrequent number of times these operations are performed, and the expense of programming.

25 The first off-line test to be performed placed voltage on the cable using a variable ac voltage power supply. Using the power supply, voltage was applied one phase at a time to 11-12 kV and held for 30 minutes to test the cable dielectric system. Phases 1 and 2 were maintained at 166% of rated voltage without breakdown. Phase 3, which has a slightly different geometry, was maintained at 230% of rated voltage without  
30 breakdown.

During the test, the charging current was measured from which the cable capacitance was determined and compared to the calculated capacitance as shown in Table 6. The calculated cable inductance is also shown. The cable surge impedance is 4  $\Omega$  which  
35 is lower than a conventional copper cable. With this lower surge impedance, the ac superconducting cable has a longer critical length (length at which charging current

5 equals rated current) when compared to a conventional copper cable. Thus the superconducting cable can be run in longer continuous lengths before the charging current dominates the cable's current carrying capability.

10

TABLE 6  
MEASURED AND CALCULATED CAPACITANCE

	Phase 1	Phase 2	Phase 3
Capacitance – nF / m			
Measured	1.815	1.739	1.265
Calculated	1.778	1.778	1.207
Difference	2.1%	-2.2%	4.8%
Inductance – nH/m			
Calculated	31.4	31.4	38.2
The above values result in a surge impedance for the 30-m cable of about 4 ohms.			

15

To measure the dc voltage vs. current relationship (V-I curve) of the cable, a 3000 A dc power supply was provided. Voltage taps were temporarily installed external to the main and shield bushings. The V-I curve was measured two phases at a time by connecting the dc power supply on two phases at one end and a short jumper between the phases at the other end. Phase 2 and 3 were measured, then phase 1 and 2, so phase 2 was measured twice. The V-I curves of the main conductors were measured, and then the shield conductor, as the cable is the cold dielectric design with coaxial

20

25

The dc voltage/current tests were repeated in June 2000 to determine cable performance after 6 months of operation after 4 to 6 cool-down and warm-up cycles, and operating under variable loading conditions. As shown in Fig. 30, there has been no change in the superconducting cable performance.

30

DC load current tests were conducted to simulate average, rated, and emergency loading on the superconducting cables. As shown in Fig. 31, the extended load

5 current tests were run at ~800, 1200 and 1400 A each for 8 hours on the two of the main conductors at a time using the dc power supply. No changes in cable cooling system temperatures were observed during these initial loading tests.

10 The next test was an extended, open-circuit, rated-voltage test using the substation supply. The cable breaker at one end was closed and the other end remained opened, so no current was flowing through the cable. Phase voltage was maintained on each phase in several sequences up to 12 hours. The cable dielectric performance was as designed.

15 The liquid nitrogen return leg temperature variation for phase 1 is shown in Fig. 32 (note, the y-axis value is not shown). The variation in the cable temperature is about 1 K.

20 The return leg liquid nitrogen pressure for phase 1 is shown in Fig. 33 (note, the y-axis value is not shown). The variation in the cable pressure is about 0.28 bar (4 psi).

Several cryogenic heat loads tests have been conducted and the total cable system heat loss has been measured. The heat loss for all 3 phases of the 30-m cable and terminations at 600 A was found to be 1490 W. The various components have been  
25 measured directly or separately, so a breakdown of the heat loss can be estimated. For each cable termination, the heat loss is 230 W and there are six terminations. The cable cryostats, each a 7.62 cm × 12.7 cm (3" × 5") vacuum jacketed pipe, are 1 W/m/phase. At 600 A, the conductor and shield accounted for 0.2 W/m/phase.

30 Although the present invention has been described and illustrated in detail, it is clearly understood that the same is by way of illustration and example only and is not to be taken by way of limitation, the spirit and scope of the present invention being limited only by the terms of the appended claims.



5 What is claimed is:

1. A cable employing an oxide superconductor, comprising:

a flexible core member;

10 a plurality of tape-shaped oxide superconducting wires being laid on said core member with tension of not more than 2 kgf/mm<sup>2</sup> wherein each tape-shaped superconducting wire consisting essentially of an oxide superconductor and a stabilizing metal covering the same,

15 said plurality of tape-shaped superconducting wires forming a plurality of layers each being formed by laying a plurality of said tape-shaped superconducting wires in a side-by-side manner,

said plurality of layers being successively stacked on said core member without an insulating layer between the plurality of layers and the core member,

20

said core member providing said superconducting cable with flexibility,

said superconducting cable capable of maintaining a superconducting state at the temperature of liquid nitrogen,

25

said wires having substantially homogeneous superconducting phases along the longitudinal direction of said wire,

30 the c-axes of said superconducting phases being oriented substantially in parallel with the direction of thickness of said wire,

said superconducting wires being formed by grains aligned in parallel extending along the longitudinal direction of said wire,

said grains being stacked along the direction of thickness of said wire.

35

- 5     2. The superconducting cable of claim 1 having flexibility such that the superconductivity of said cable does not substantially deteriorate upon bending up to about 50 times the diameter of the cable.
- 10     3. The superconducting cable of claim 1, wherein said core member is selected from the group consisting essentially of metals, plastics, reinforced plastics, polymers, and composites.
- 15     4. The superconducting cable of claim 1, wherein said core member is a pipe having a surface selected from a spiral groove surface, a web shaped surface, a braid surface, and a mat shaped surface on its exterior which forms a surface for the tape-shaped superconducting wires.
- 20     5. The superconducting cable of claim 1, wherein an insulating layer is not present between the plurality of layers.
- 25     6. The superconducting cable of claim 5, wherein after the first layer of tape-shaped wires are laid on said core member the subsequent tape-shaped plurality of layers are laid on the surfaces formed by the immediately prior layer of tape-shaped wires.
- 30     7. The superconducting cable of claim 1, wherein said wires are twisted within said tape-shaped stabilizing metal covering.
- 35     8. The superconducting cable of claim 1, wherein said tape-shaped wires are laid at a lay angle of up to about 90 degrees.
9. The superconducting cable of claim 8, wherein said tape-shaped wires are laid at a lay angle of from about 10 to about 60 degrees.
10. The superconducting cable of claim 9, wherein said tape-shaped wires are laid at a lay angle of from about 20 to about 40 degrees.

5 11. The superconducting cable of claim 1, further including at least two distinct groups of tape-shaped wire layers.

12. The superconducting cable of claim 11, wherein the lay angle of each successive layer of tape-shaped wires alternate in lay direction or pitch.

10

13. The superconducting cable of claim 12, wherein each said successive layer consists of at least two tape-shaped wires for a construction of four or more even layers.

15 14. The superconducting cable of claim 11, wherein a layer of dielectric material separates each of the at least two distinct groups of tape-shaped wire layers.

15. The superconducting cable of claim 11, wherein a layer of dielectric material separates the core member from the layer of tape-shaped wires closest thereto.

20

16. The superconducting cable of claim 14, wherein the dielectric material is selected from the group consisting of polypropylene, polyethylene and polybutylene.

17. The superconducting cable of claim 11, wherein the at least two distinct groups of  
25 tape-shaped wire layers carries approximately equal amounts of the current flowing through the cable.

18. The superconducting cable of claim 11, wherein the first of the two distinct groups of tape-shaped wire layers carries greater than 50 percent of the current  
30 flowing through the cable.

19. The superconducting cable of claim 11, wherein the second of the two distinct groups of tape-shaped wire layers carries greater than 50 percent of the current flowing through the cable.

35

- 5 20. The superconducting cable of claim 17, wherein the group of tape-shaped wire layers furthest from the core member provides shielding of the current flowing through the other layers and reduces magnetic fields or eddy currents in the cable.
21. The superconducting cable of claim 1, wherein the stabilizing metal is selected  
10 from the group consisting of silver, silver alloys, nickel and nickel alloys.
22. The superconducting cable of claim 1, wherein each of said plurality of layers contains at least 2 tape-shaped wires per layer.
- 15 23. The superconducting cable of claim 1, wherein each of said plurality of layers contains at least 4 tape-shaped wires per layer.
24. The superconducting cable of claim 23, including an insulating layer between the second and third layer of said plurality of layers.  
20
25. The superconducting cable of claim 23, including an insulating layer between each second and third layer of said plurality of layers.
26. The superconducting cable of claim 14, wherein the dielectric material has a  
25 maximum dielectric constant of about 3.0
27. The superconducting cable of claim 26, wherein the dielectric material has a maximum dielectric constant of about 2.3.
- 30 28. The superconducting cable of claim 14, wherein the dielectric material is biaxially oriented at a ratio of from about 5:1 to about 10:1 in the machine direction.
29. The superconducting cable of claim 28, wherein the dielectric material is biaxially oriented at a ratio of from about 5:1 to about 6:1 in the machine direction.  
35

5 30. The superconducting cable of claim 28, wherein the dielectric material is further biaxially oriented up to about 2:1 in the cross machine direction.

31. The superconducting cable of claim 28, including embossing the biaxially oriented dielectric material so as to form irregular and/or random channels therein.

10

32. The superconducting cable of claim 31, wherein the dielectric material is embossed with channels having a depth of from about 0.5 to about 2 ml.

15 33. The superconducting cable of claim 31, wherein the embossing is performed by a roller at a temperature from about 80°C to about 140°C.

34. The superconducting cable of claim 30, wherein the dielectric tape is embossed in a pattern which preferentially permits impregnant flow across the tape width.

20 35. The superconducting cable of claim 31, wherein the dielectric tape is embossed in a pattern of irregular hills and valleys running across the tape.

25 36. The superconducting cable of claim 14, wherein the dielectric tape is produced from material which contains organic color dye in a quantity within the range of 100 to 1000 parts per million.

37. The superconducting cable of claim 31, wherein the dielectric tape is embossed in a pattern which increases the effective tape thickness.

30 38. The superconducting cable of claim 31, wherein the dielectric tape is embossed in a pattern with up to about 0.2mm spacing between the adjacent peaks.

39. The superconducting cable of claim 38, wherein the dielectric tape is embossed in a pattern with up to about 0.05mm spacing between peaks.

35

5     40. The superconducting cable of claim 14, wherein the dielectric tape has a tensile modulus of at least 250,000 psi.

41. A superconducting cable for alternating current having phase and neutral conductors cooling channels and an outer encircling insulation, wherein a common  
10     neutral is provided for all three phase conductors and the cooling channels are arranged concentrically together.

42. A superconducting cable according to Claim 41 wherein the first phase conductor of the cooling channel is bounded by the conducting cable core and an insulation  
15     layer of defined thickness is provided between the first and the second phase conductors, the second and the third phase conductors and between the third phase conductor and the neutral conductor respectively, a cooling channel is provided as an annular channel between the neutral conductor and the outer insulation and the phase conductors are manufactured of a superconducting material.

20

43. A superconducting cable according to Claim 41 wherein each phase conductor is manufactured of superconducting tapes, which consist of flat rolled sleeves of an oxygen-porous metal filled with a ceramic superconducting material.

25     44. A superconducting cable according to Claim 41 wherein the phase conductors are manufactured as tapes comprised of silver sleeves filled with a ceramic superconducting material.

45. A superconducting cable according to Claim 41 wherein liquid nitrogen is  
30     conducted through channels for cooling of the superconducting phases.

46. A superconducting cable according to Claim 41 wherein the neutral conductor is manufactured of copper.

35     47. A superconducting cable according to Claim 41 wherein the insulation layers between the phase conductors are manufactured of polyethylene or polypropylene.

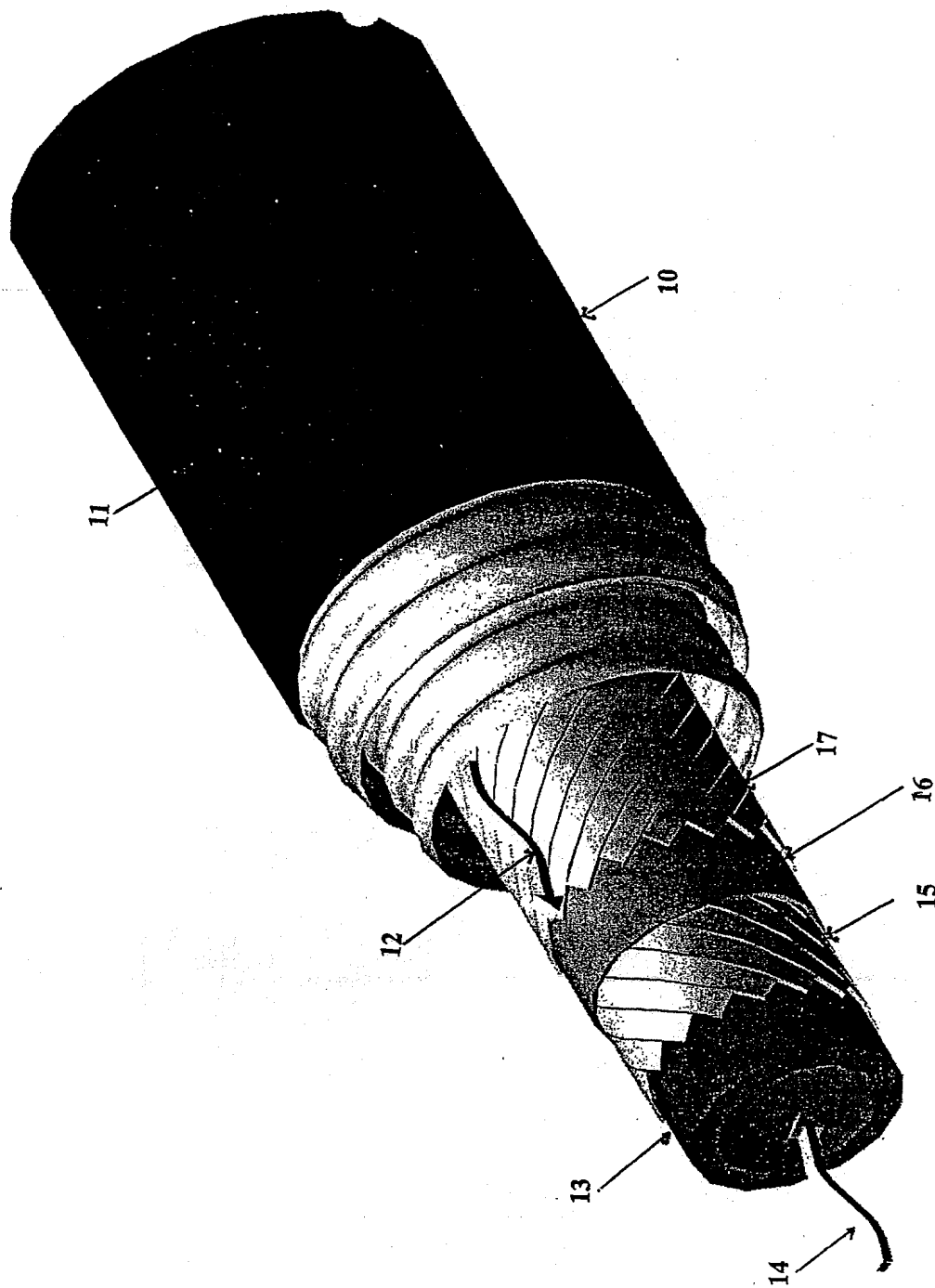


FIGURE 1

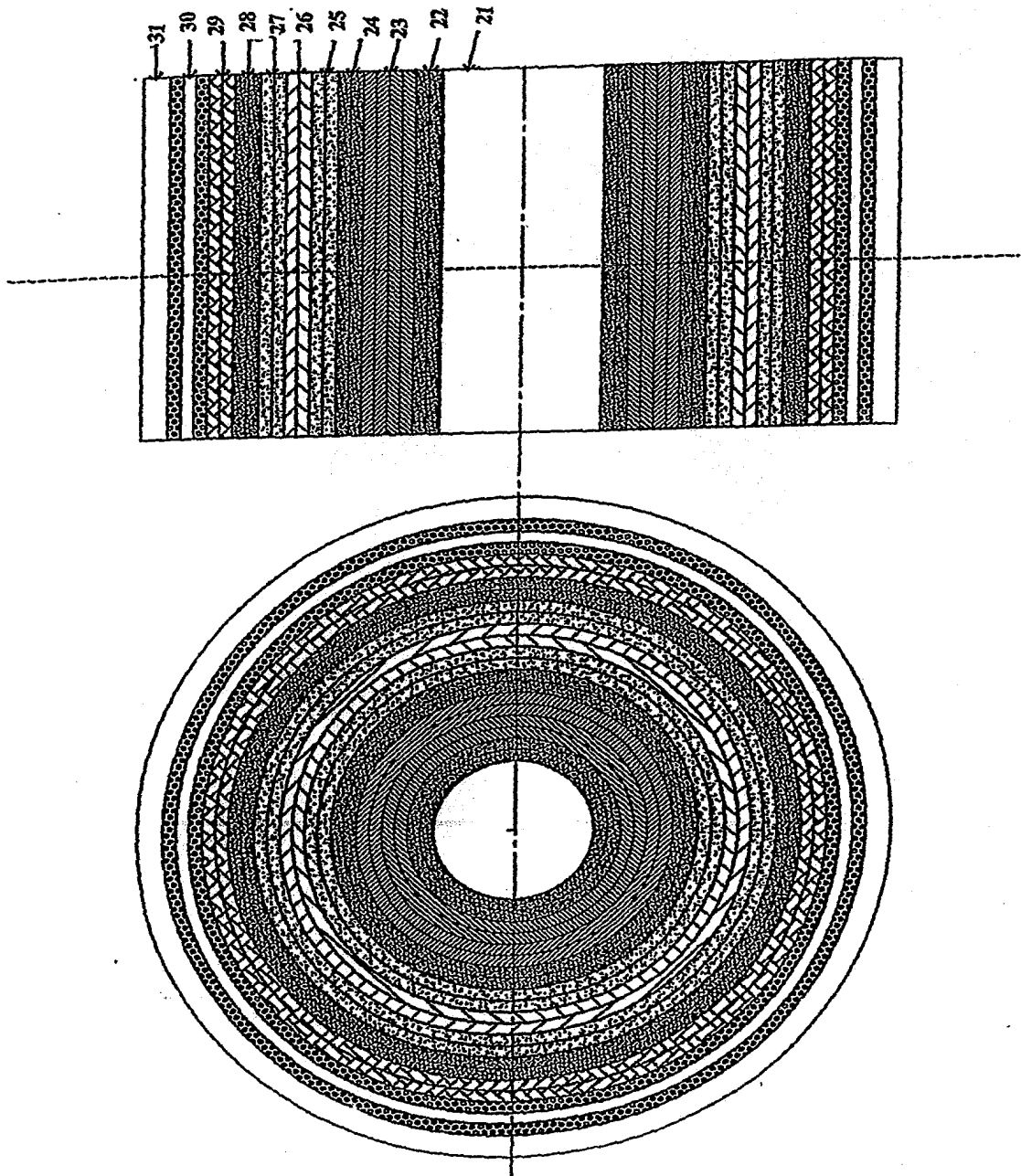


FIGURE 2



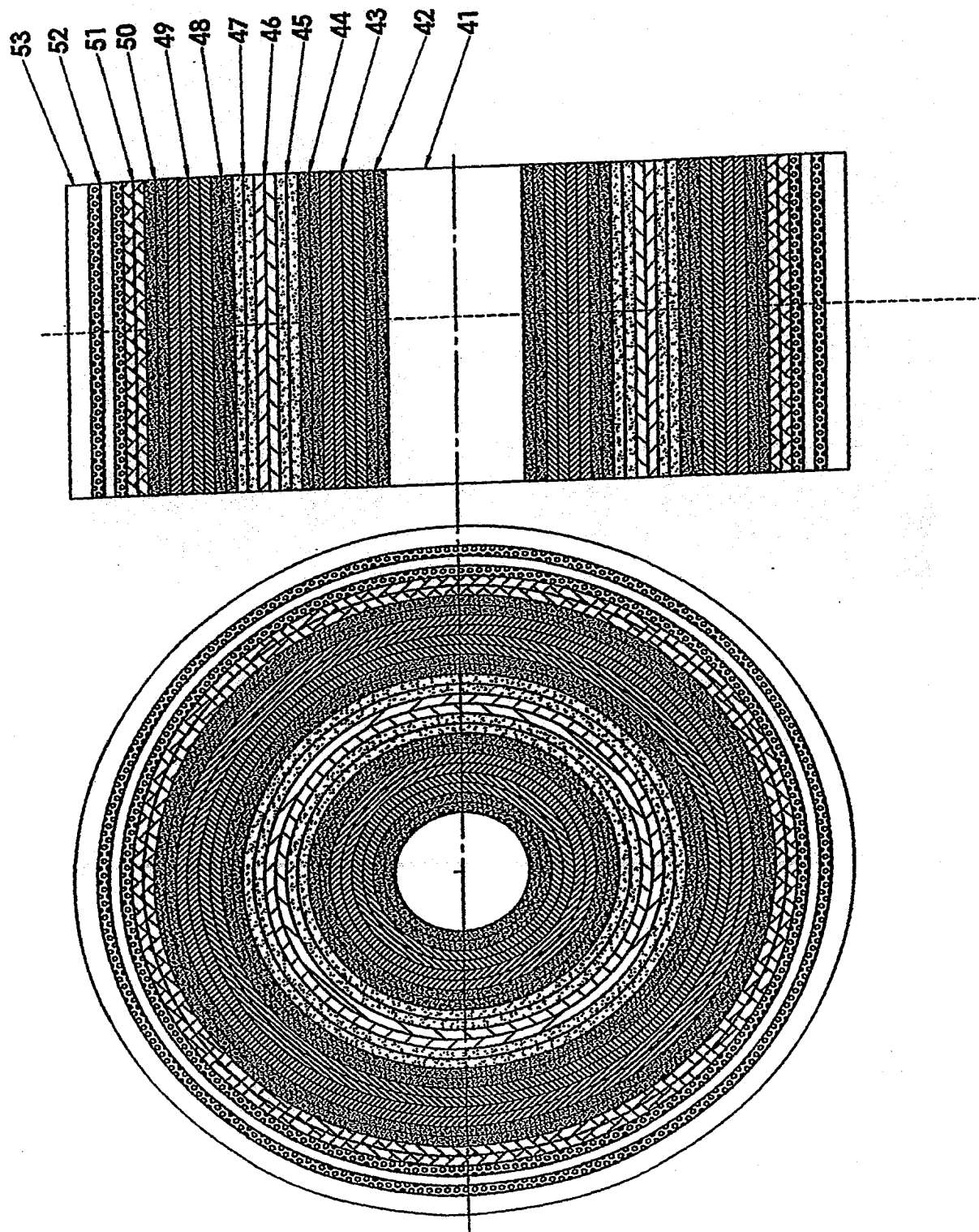
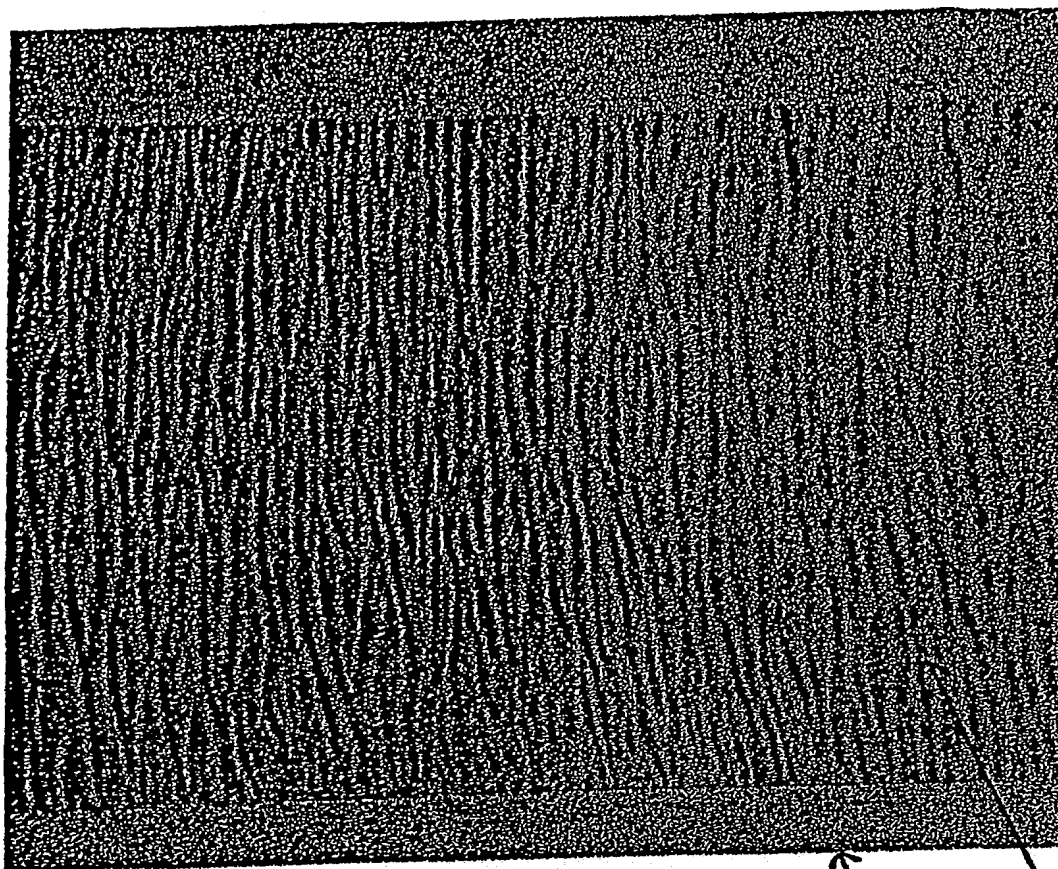


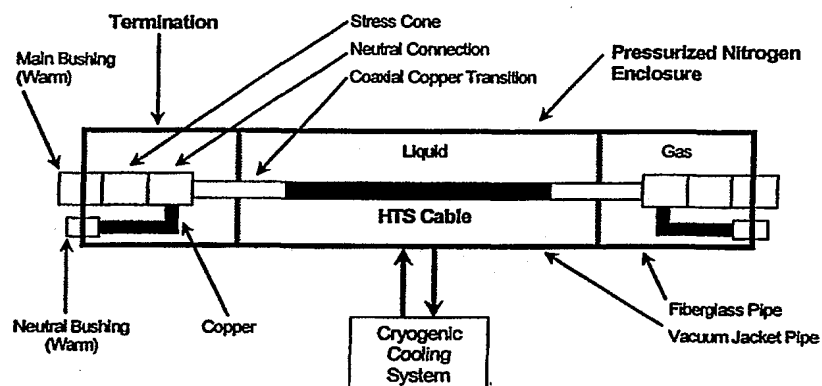
FIGURE 3



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**FIGURE 4**

**FIGURE 5**



**FIGURE 6**

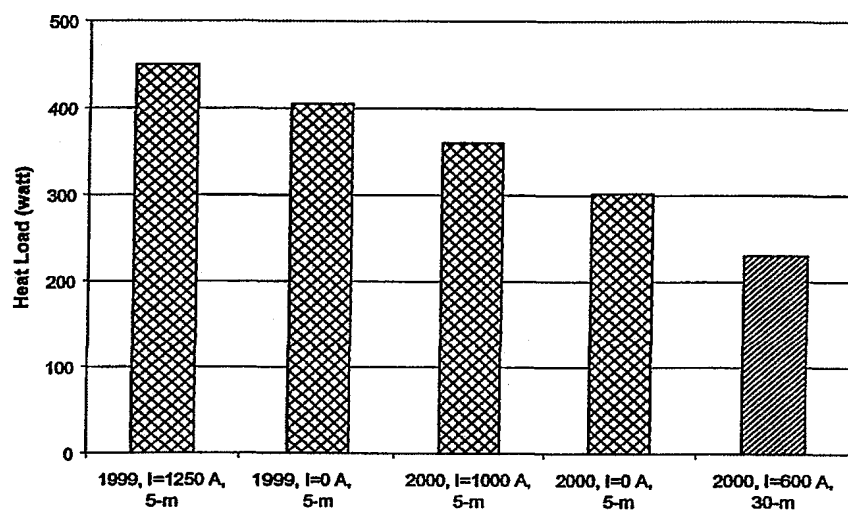


FIGURE 7

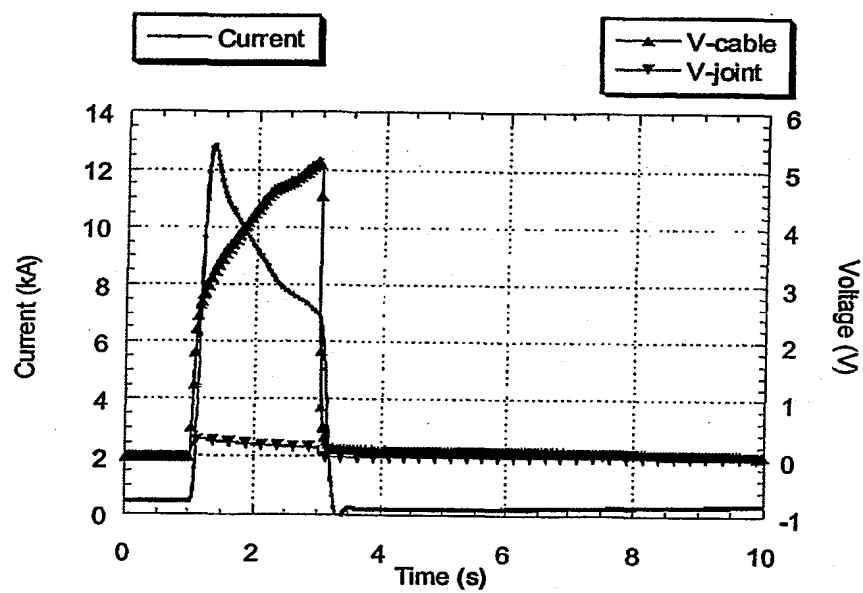


FIGURE 8

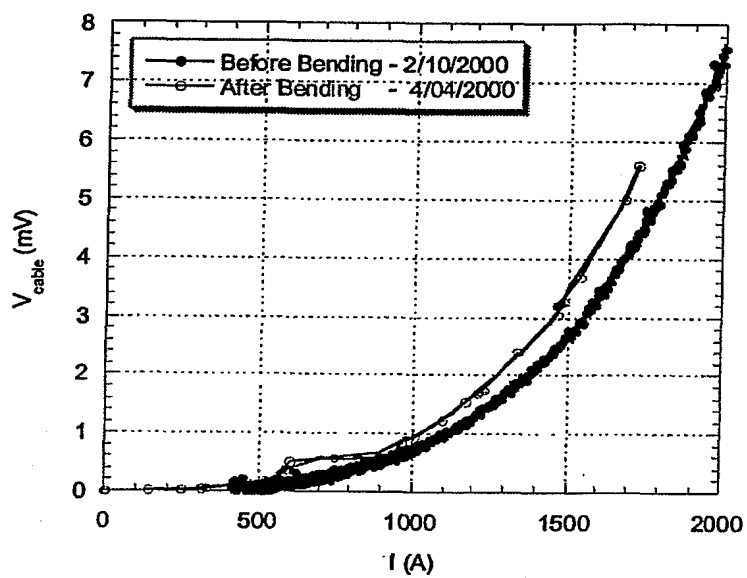


FIGURE 9

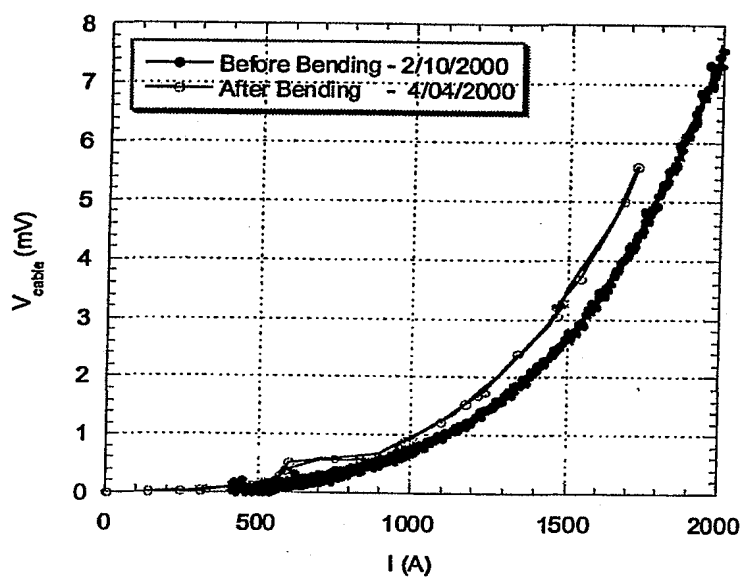
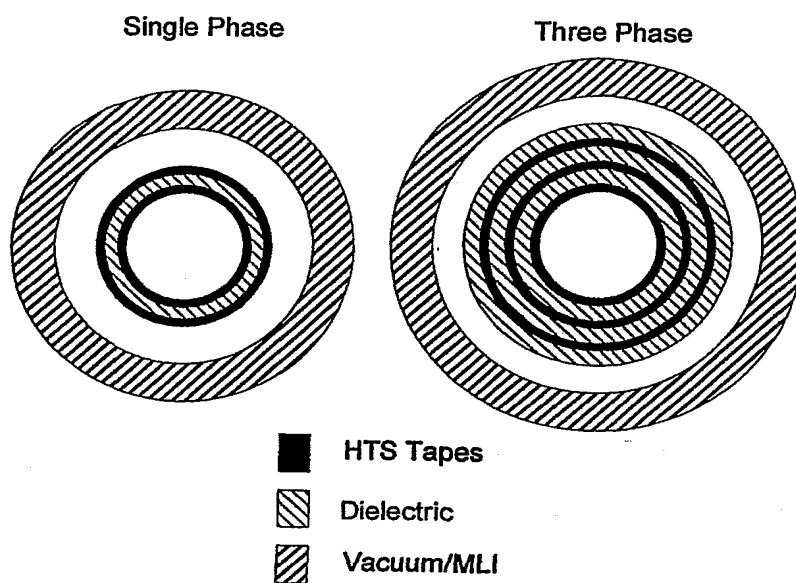


FIGURE 10





**FIGURE 11**

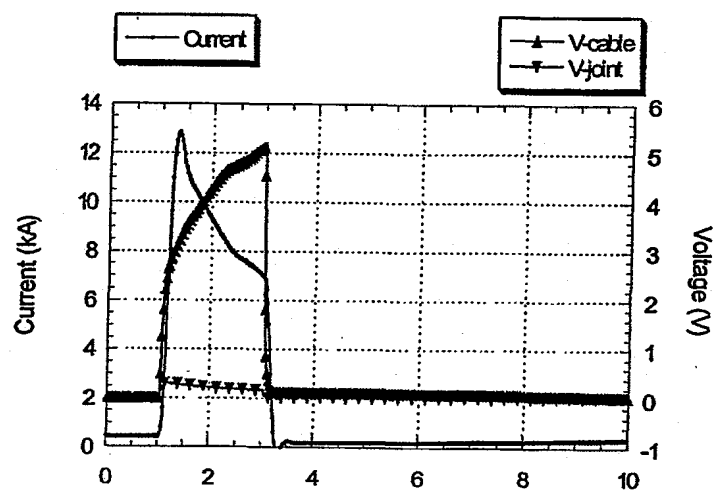


FIGURE 12

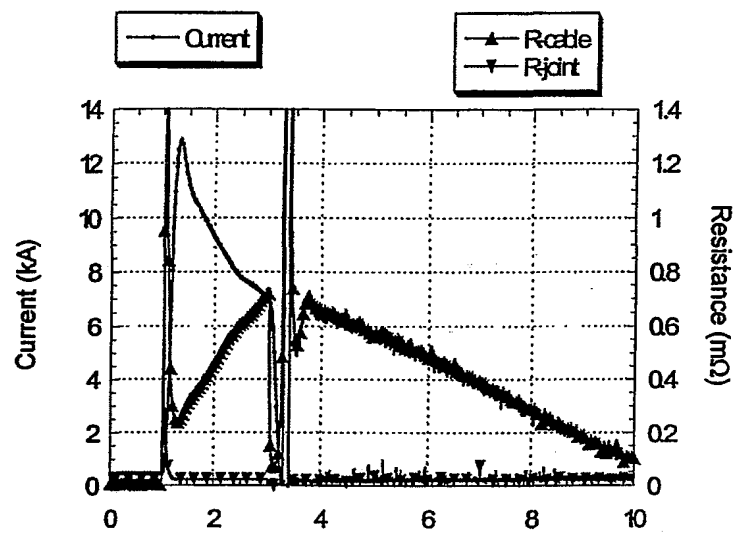


FIGURE 13

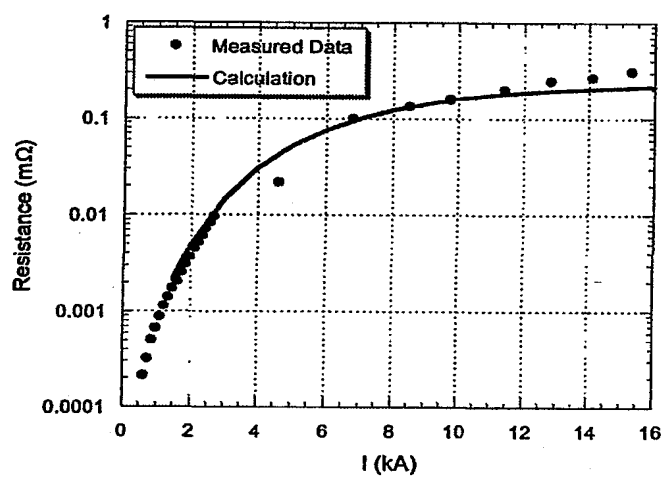


FIGURE 14

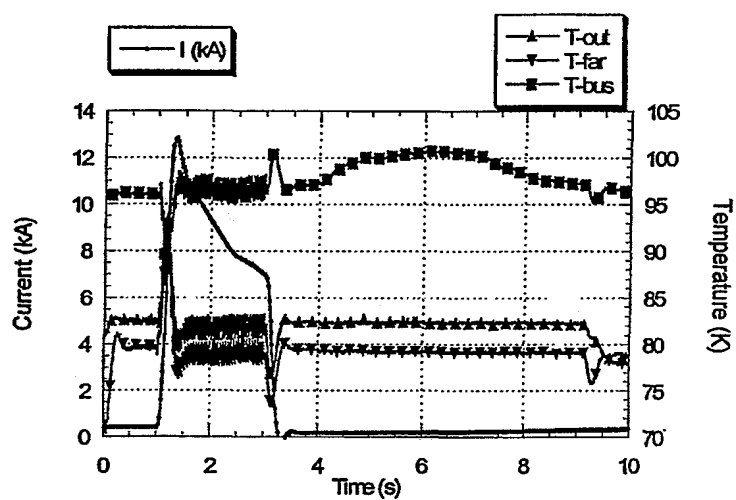


FIGURE 15

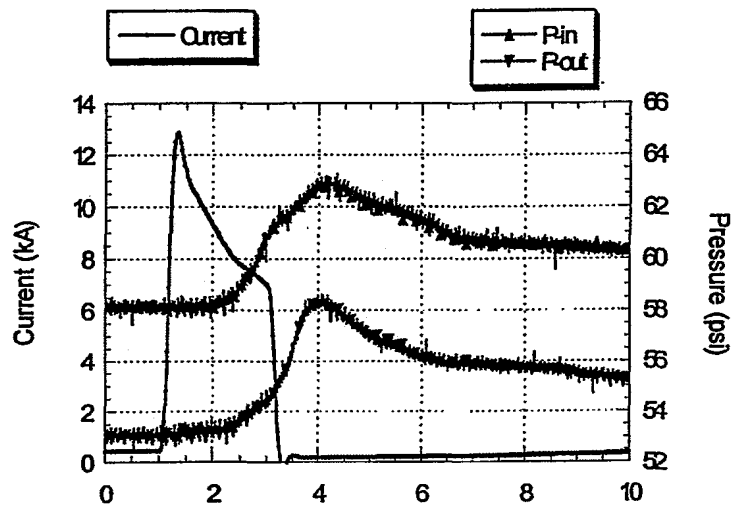


FIGURE 16

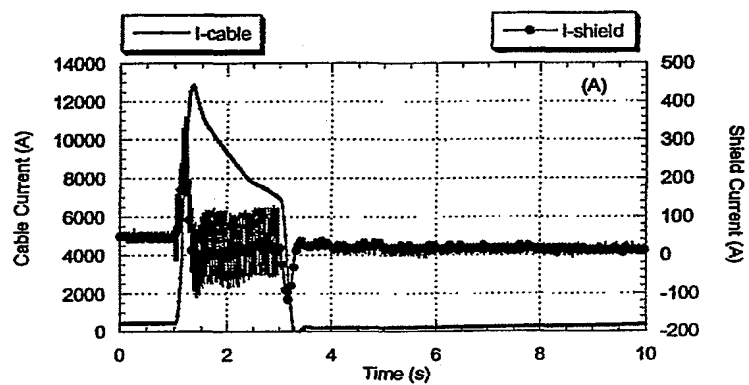


FIGURE 17A

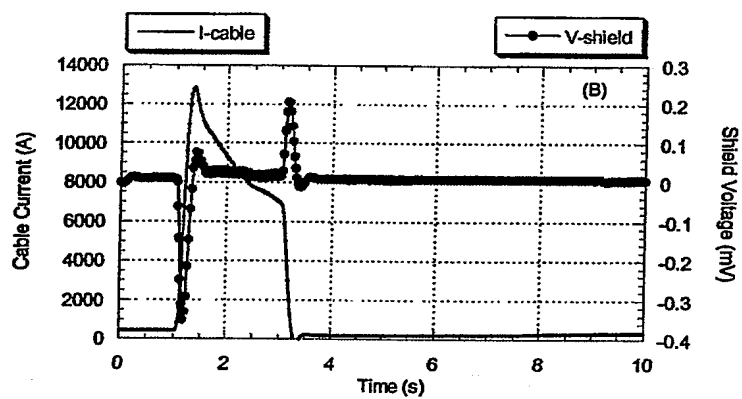


FIGURE 17B



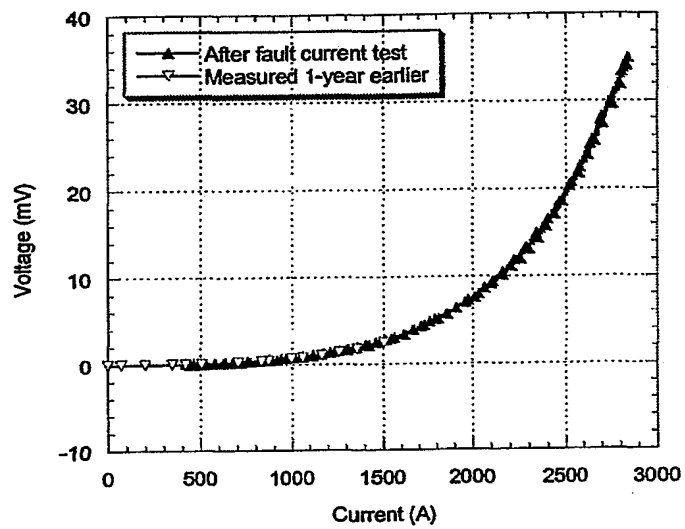
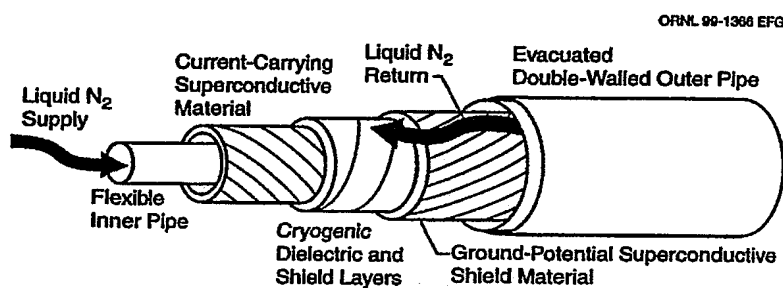


FIGURE 18

**FIGURE 19**

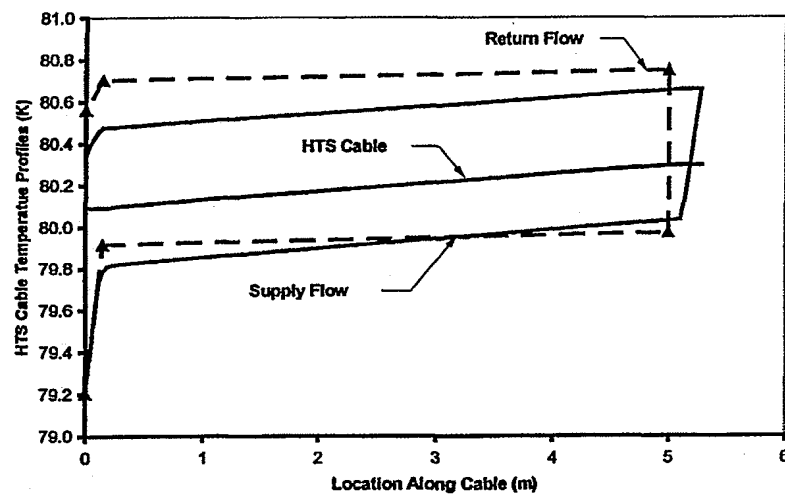


FIGURE 20

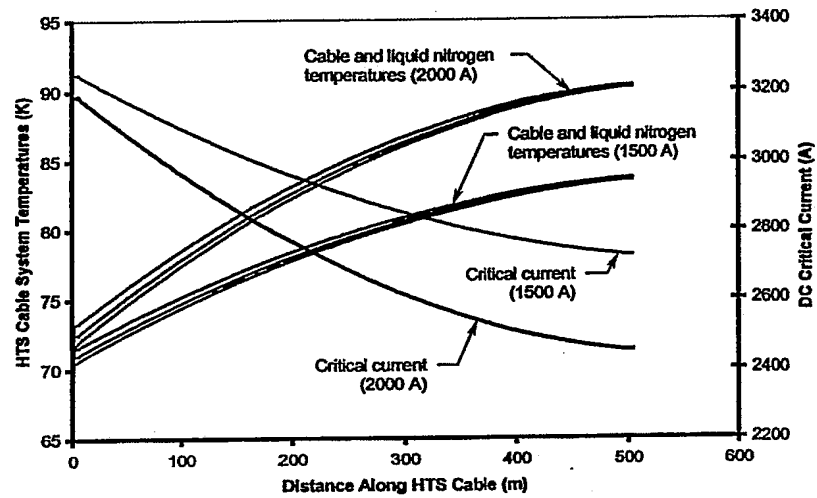


FIGURE 21

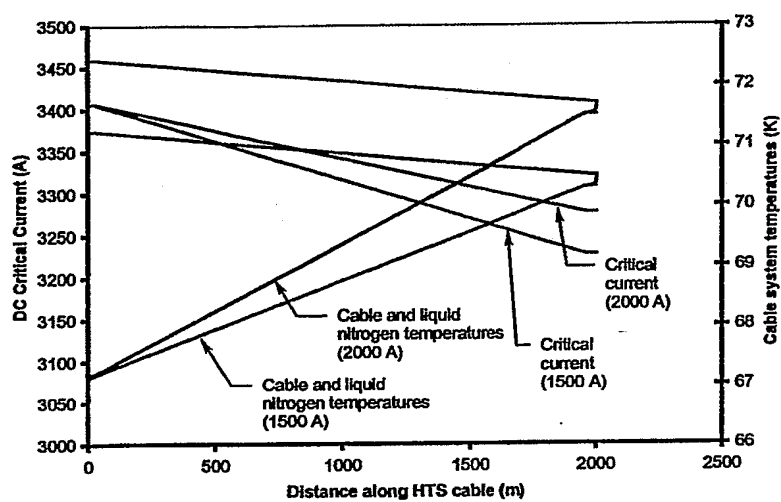


FIGURE 22

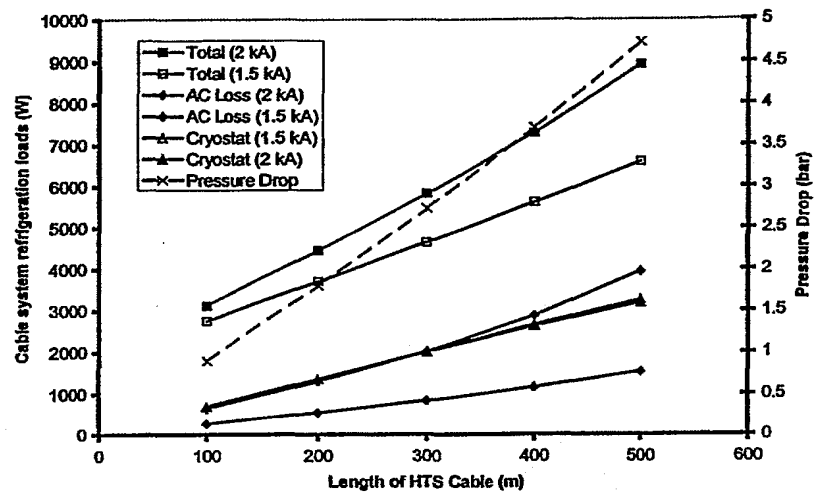


FIGURE 23

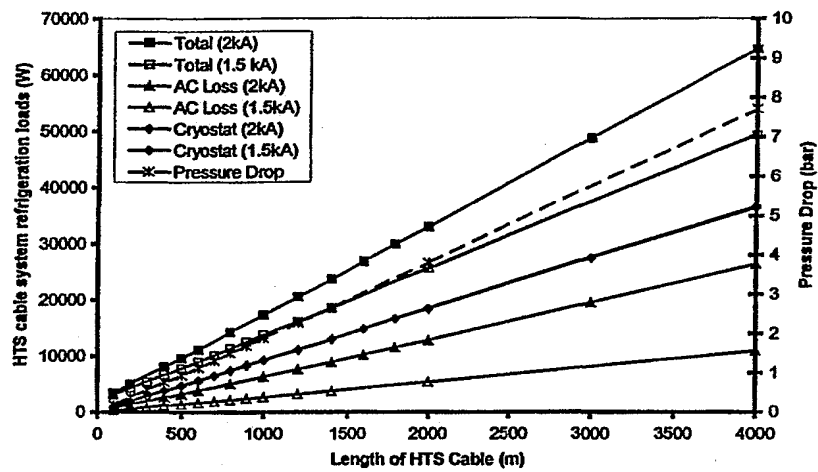


FIGURE 24

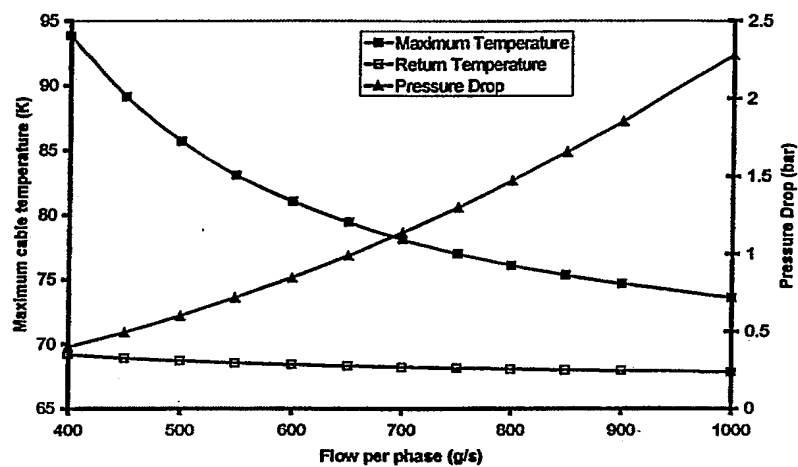


FIGURE 25



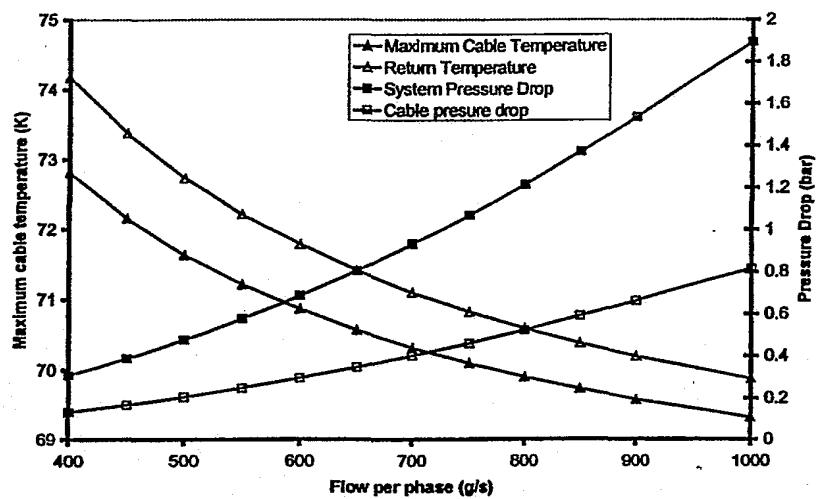


FIGURE 26

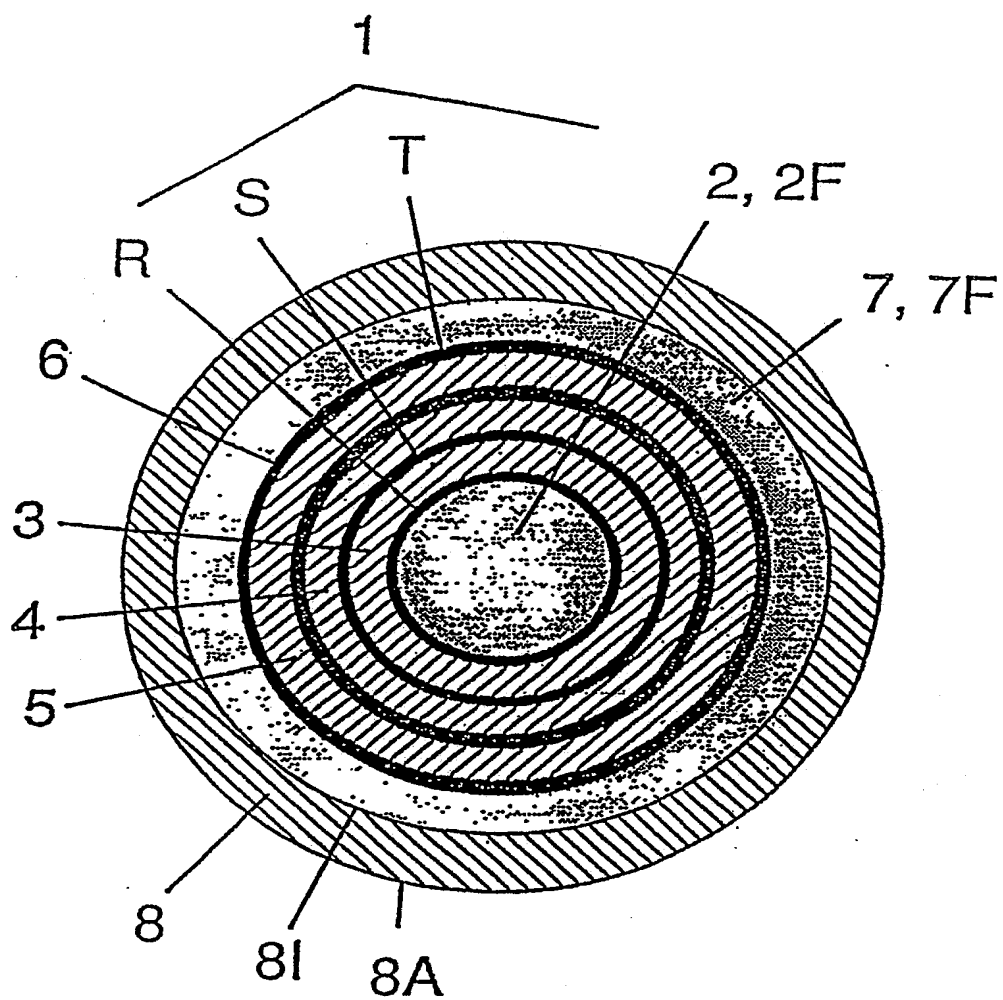


FIGURE 27

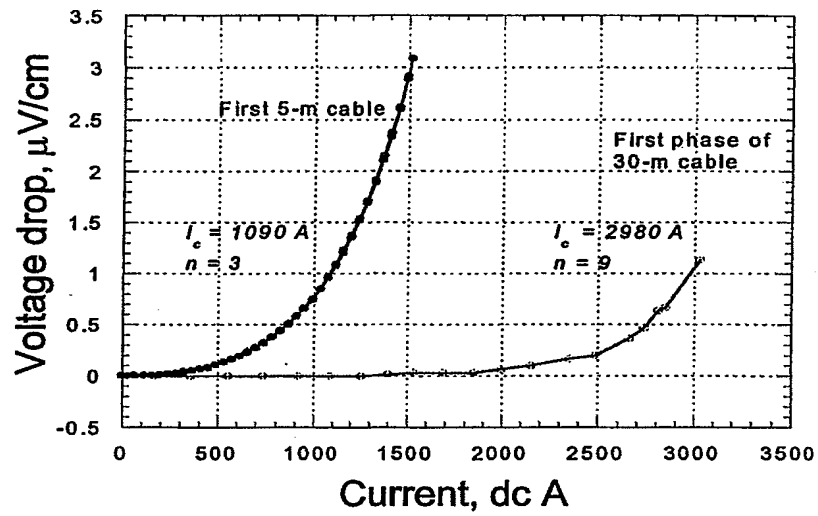
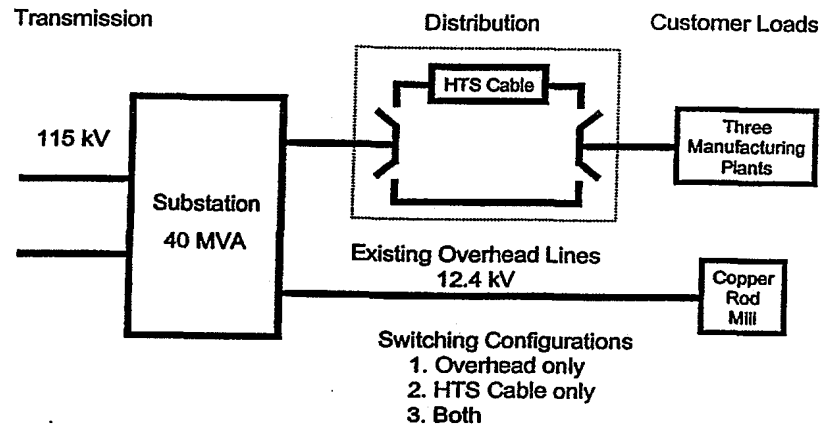
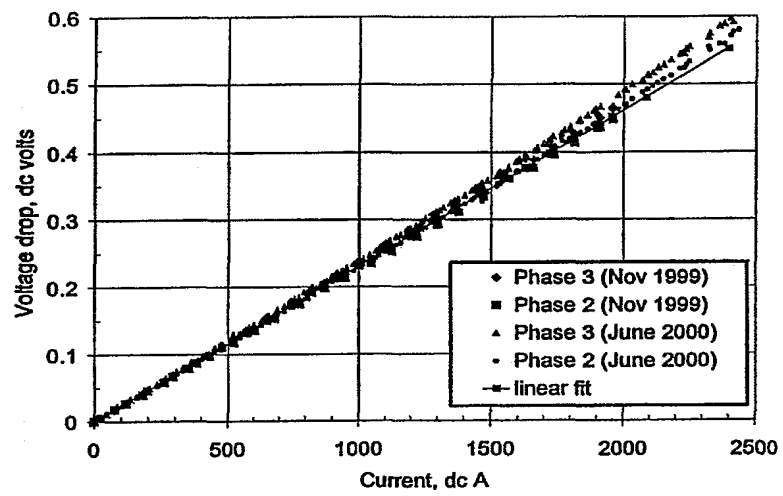
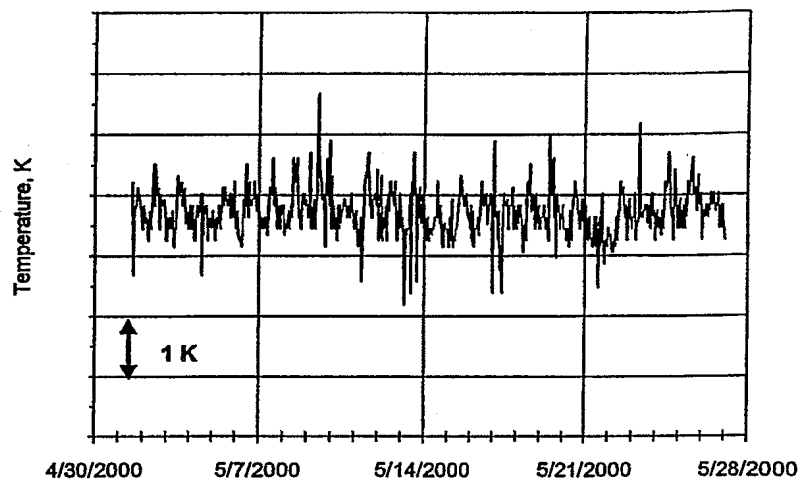


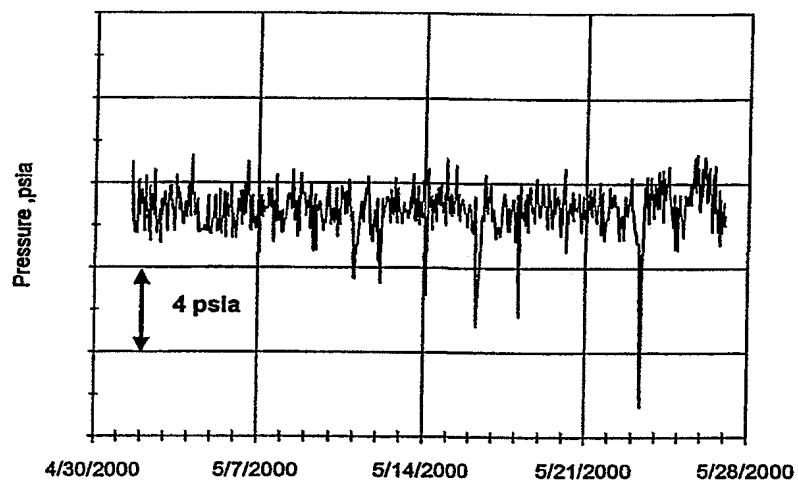
FIGURE 28

**FIGURE 29**

**FIGURE 30**



**FIGURE 32**

**FIGURE 33**



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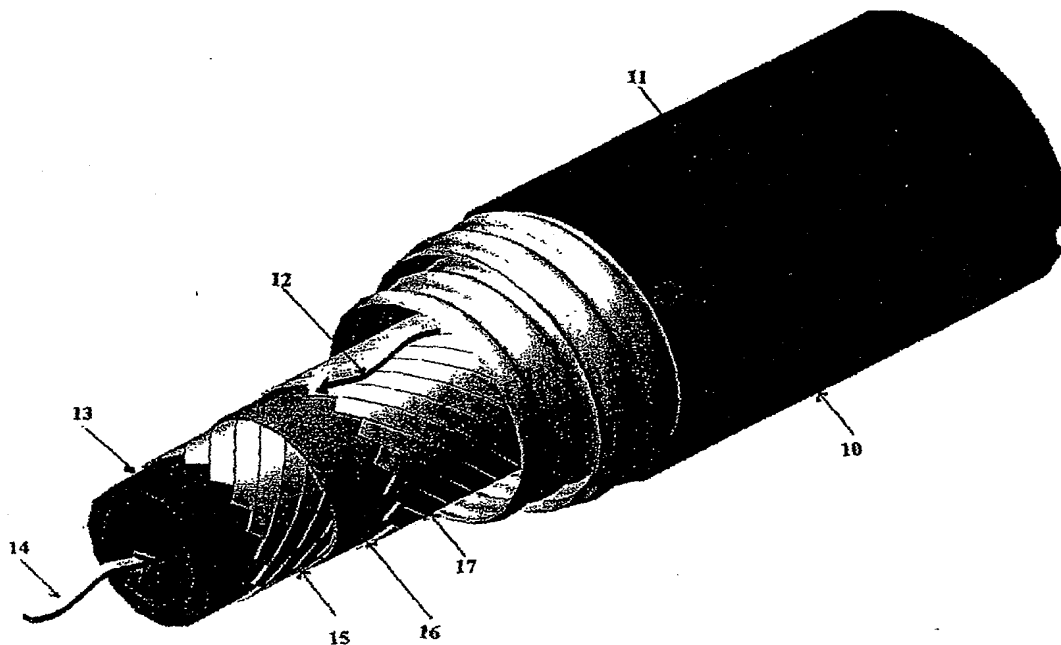
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[Continued on next page]

(54) Title: SUPERCONDUCTING CABLE



(57) Abstract: Tape shaped superconducting wires are covered with a stabilizing metal and are wound on a flexible former (13). The wires are laid at a bending strain of not more than 0.2 %. A number of wires are laid in a side-by-side manner to form a first layer (15). Tape shaped superconducting wires are laid on top of the first layer in a side-by-side manner to form a second layer. The former may be metal, plastic, reinforced plastic, polymer or a composite and provides flexibility to the superconducting wires and the cable formed therewith.

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patent (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM), European patent (AT, BE, CH, CY, DE, DK, ES, FI, FR, GB, GR, IE, IT, LU, MC, NL, PT, SE, TR), OAPI patent (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, ML, MR, NE, SN, TD, TG).

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# INTERNATIONAL SEARCH REPORT

International application No.

PCT/US01/28630

## A. CLASSIFICATION OF SUBJECT MATTER

IPC(6) : H01B 12/00

US CL : 174/125.1

According to International Patent Classification (IPC) or to both national classification and IPC

## B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

U.S. : 174/125.1; 505/230,231,704,886,887

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

## C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 5,932,523 A (FUJIKAMI et al.) 03 August 1999 (03.08.1999)	1-5
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Y		11, 14
Y	US 5,952,614 A (RIES) 14 September 1999 (14.09.1999)	11, 14
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A		1-10, 12-13, 15-47
A	US 3,612,742 A (SNOWDEN et al.) 12 October 1971 (12.10.1971)	1-47
A	US 3,730,966 A (AUPOIX et al.) 20 January 1972 (20.01.1972)	1-47
A	US 3,292,016 A (KAFKA) 13 December 1966 (13.12.1966)	1-47
A	US 3,643,002 A (MINNICH) 15 February 1972 (15.02.1972)	1-47

☐ Further documents are listed in the continuation of Box C.

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"&"

document member of the same patent family

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